



PHD

Future-Oriented Energy and Environmental Assessment of the UK Power System and Associated Technologies

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Award date:
2016

Awarding institution:
University of Bath

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Future-Oriented Energy and Environmental Assessment of the UK Power System and Associated Technologies

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A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department of Mechanical Engineering

July 2016

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Abstract

Electricity sector decarbonisation is widely seen as a fundamental step in the global fight against climate change. The need to secure this transition is compounded by the prospective use of electrification to deliver economy-wide carbon reductions, especially in harder to address sectors like heat and transport. No agreement has yet been reached on the best decarbonisation approach. Empirical evidence is required to guide a transition that not only succeeds in delivering a ‘truly’ low carbon electricity source, but also prevents wider environmental issues being exacerbated.

This research portfolio examines the low carbon transition of electricity systems in a UK context. The energy and environmental implications in response to different decarbonisation approaches were evaluated using Life Cycle Assessment (LCA) and related methods. Potential UK low carbon electricity systems were investigated *via* three socio-technical energy scenarios, known as the *Transition Pathways*. Key factors were identified, which may impact the future environmental performance of UK electricity, such as supply chain dynamics, policy shifts, and new entrant technologies, were investigated to assess their consequences on decarbonisation targets. This research exemplifies the guiding principles of LCA as a valuable proactive tool in shaping superior future decarbonisation and wider environmental policies.

A key finding of this thesis was the importance of whole life cycle accounting of power sector GHG emissions, including upstream impacts which are often overlooked by governmental bodies. Hence, current decarbonisation policies may lead to a shift in practices and the adoption of production routes with unintended negative effects upstream. In this work, the upstream gas emissions for future supplies increase significantly (rising 2.7 to 3.4 times current mix per MJ supplied) and are foreseen to be highly influential on the future electricity systems analysed. Increased influx of biomethane leads to a substantial reduction in direct fossil emissions (up to 10.6 million tonnes of CO₂eq), and is found to be critical in offsetting rising upstream emissions. The roll-out of carbon capture and storage was also found to be instrumental in the success of the pathways.

The electricity system transitions assessed achieved differing, yet significant, levels of decarbonisation (between 75-85% reductions on 1990 levels on a lifecycle basis). Nevertheless, these were often achieved at the expense of wider environmental impacts, suggesting trade-offs were unavoidable. The civic-led energy transition resulted in the greatest associated environmental benefits, realising the greatest reduction in 13 of 18 environmental categories assessed, compared to the 2008 levels. It was also the only pathway to decouple electricity supply from fossil fuel use. Reliance on metal resources was seen to steadily increase in response to a developing renewable energy sector, rising 23-75% from the 2008 baseline system. The presented results, models and data are transparently presented for others in the field to build upon, and scrutinise their implications for wider decarbonisation strategies within and outside of the electricity sector.

Acknowledgements

I would firstly like to acknowledge the UK Engineering and Physical Sciences Research Council for funding my role as a Research Associate as part of the *Realising Transition Pathways* project. Thanks to Professor Geoffrey Hammond for the opportunity to work on this project, and for developing the project and securing its funding.

A big thank you to Sally Clift for her excellent guidance and support over the course of drafting this thesis, and for the positive energy she brought to all of our meetings.

Thank you to all the members of the Sustainable Energy Research Team (SERT), and the other researchers in 8 East, for making the University of Bath a far more enjoyable place to work. A special thanks to Dr Marcelle Mc Manus, who was always willing to offer support and guidance, despite having absolutely no obligation to do so. This journey may have never begun without your input, for which I am extremely grateful.

Thank you to all the members of the *Realising Transition Pathway* consortium, especially the ‘engine roomers’. My development as an energy researcher was greatly enhanced through our interaction. I will greatly miss our engine room meetings which were very fulfilling, both professionally and personally. Particular thanks go to the co-authors of the seven research articles submitted as part of this thesis. This would not have been possible without your vital support and contribution.

Mum and Dad, your encouragement and relentless faith, gave me the necessary strength to keep going. Thank you for the endless love and support, and for being available at a moment’s notice on facetime for those times when I needed you most. This would definitely not have been possible without you both. I feel so incredibly blessed to be your daughter. Dad, thanks also for all the proof reading... I probably owe you another trip to Turnberry.

Thanks to Mamó for providing me with my first true example of an environmentalist. Your unyielding zest for knowledge and capacity to learn, have been inspirational to say the least.

To Liam, Eoghan, David and the rest of my family and friends in Ireland, thank you for all your love and support, and making my trips back home so relaxing and special. I particularly want to thank my brother David, and my beautiful nieces Clodagh and Aoibhínn for keeping my perspective on life in check.

My last and biggest thanks go to Glyn. You have supported me day in and day out through this entire process, right up to the final hour. I cannot thank you enough for all the love, encouragement and patience you have shown me over this time. You truly have been the ultimate *domestique*. Your crazy sense of adventure, and joie de vivre never failed to make me smile when I was in need. I could not have done it without you I think we definitely need that holiday now.

Table of Contents

Table of Contents	v
1 Introduction	1
1.1 Research Context	1
1.2 Global Approach to Tackling Climate Change	1
1.3 UK Approach to Tackling Climate Change	3
1.4 Energy Scenarios and the Transitions Pathways	4
1.5 Scope of Research	10
1.6 Research Aim and Objectives	11
2 Methods and Research Approach	12
2.1 Life Cycle Assessment	12
2.1.1 Application of LCA to energy systems	12
2.1.2 Evolution of LCA	13
2.1.3 Attributional LCA approach	15
2.1.4 Consequential LCA approach	17
2.1.5 Allocation of emissions	20
2.1.6 Life Cycle Impact Assessment methodology	21
2.2 Carbon Footprinting	24
2.3 Energy Analysis	25
3 Research Commentary	27
3.1 Introduction	27
3.2 Commentary Overview	27
4 Article I - ‘Environmental life cycle assessment (LCA) of energy systems’	29
4.1 Book chapter	29
4.2 Contribution to Research:	29
4.3 The Significance and Originality of the Article	29
4.4 Contribution by Candidate:	29
4.5 Article I	31
4.6 Key Outputs	70
5 Article II – ‘The implications of upstream emissions from the power sector’	71

5.1	Journal Paper.....	71
5.2	Contribution to Research	71
5.3	The Significance and Originality of the Article	72
5.4	Contribution by Candidate.....	72
5.5	Article II	73
5.6	Key Outputs	88
6	Article III - ‘Linking storylines with multiple models: an interdisciplinary analysis of the UK power system transition’	89
6.1	Journal Paper.....	89
6.2	Contribution to Research	89
6.3	The Significance and Originality of the Article	89
6.4	Contribution by Candidate.....	90
6.5	Article III	91
6.6	Key Outputs.....	126
7	Article IV – ‘Reconciling qualitative storylines and quantitative descriptions: an iterative approach’	127
7.1	Unpublished Manuscript.....	127
7.2	Contribution to Research	127
7.3	The Significance and Originality of the Article	127
7.4	Contribution by Candidate.....	127
7.5	Article IV	129
7.6	Key Outputs	160
8	Article V – ‘Indicative energy technology assessment of UK shale gas extraction’	161
8.1	Journal Paper.....	161
8.2	Contribution to Research:	161
8.3	The Significance and Originality of the Article	161
8.4	Contribution by Candidate:.....	162
8.5	Article V	163
8.6	Key Outputs	191
9	Article VI- ‘The life cycle greenhouse gas implications of a UK gas supply transformation on a future low carbon electricity sector’	193

9.1	Journal Paper.....	193
9.2	Contribution to Research:	193
9.3	The Significance and Originality of the Article	193
9.4	Contribution by Candidate:.....	193
9.5	Article VI.....	195
9.6	Key Outputs	220
10	Article VII – ‘The potential environmental consequences of shifts in UK energy policy that impact on electricity generation’	221
10.1	Journal Paper	221
10.2	Contribution to Research:	221
10.3	The Significance and Originality of the Article	221
10.4	Contribution by Candidate:.....	222
10.5	Article VII.....	223
10.6	Key Outputs	249
11	Conclusions	251
11.1	Fulfilling the Objectives of this Thesis.....	251
11.1.1	To perform a critical review of the life cycle assessment methodology as applied to the evaluation of energy systems	252
11.1.2	To determine the life cycle energy, greenhouse gas (GHG) and environmental impacts of the development of a more electric UK power sector.	252
11.1.3	To highlight the environmental significance of ‘upstream emissions’, along with their technological and policy implications.....	253
11.1.4	To explore how multidisciplinary and interdisciplinary modelling approaches can inform the future development of the UK power system within a decarbonisation framework.	254
11.1.5	To examine the environmental impacts of new entrant electricity generators options which may be adopted, and their role in the decarbonisation of the UK electricity sector.	255
11.1.6	To identify areas of considerable systemic change for the future UK power system, and quantify their impact on the environmental performance of future UK electricity.	256
11.2	Novel Contribution of this Thesis	259
11.3	Recommendations	262

11.4	Future Work	264
11.5	Concluding Remarks	266
	References	267
	Appendix A: Article III.....	273
	Appendix B: Article VI.....	283
	Appendix C: Article VII	307

1 Introduction

1.1 Research Context

Modern society is heavily reliant on its energy systems in order to function on a daily basis. Society's most critical infrastructure such as transport, water supplies, waste management and telecommunications are highly interdependent with its energy infrastructure [1]. Traditionally, these energy systems have been powered using carbon based fuels, such as coal and gas, however, a transition is now underway towards more environmentally friendly options: primarily to mitigate climate change. All energy systems emit greenhouse gases (GHG) and are thereby contributing to anthropogenic climate change, although this occurs at varying levels depending on the nature of a given system, e.g. coal more polluting than gas which is more polluting than most optimally installed renewable installations per unit energy production. The International Panel on Climate Change (IPCC) concluded in their most recent report that it was "extremely likely (defined as a 95-100% likelihood) that human influence has been the dominant cause of the observed warming since the mid-20th century" [2]. The energy sector currently accounts for two thirds of all global anthropogenic GHG [3], thus, a transformation of this sector is essential if climate change is to be circumvented.

The growth of the world's electricity infrastructure has given rise to many social-economic gains, advancing civilisation to achieve more complex tasks and with less effort, but regrettably at a rather large expense to the biosphere. A recent push towards renewable generation has been witnessed in an effort to minimise this damage. In 2015, over half of the world's new power generation capacity installed comprised of renewable generators [4]. Although alternative electricity generators can help dramatically reduce such damage, they also come with their own set of dispersed environmental impacts which needs to be quantified and managed. The environmental trade-offs between electricity generating systems, which will likely occur in response to current decarbonisation policies, must be systematically evaluated. Electricity decarbonisation policies are being implemented by many countries worldwide [5]; however, due to the complexity of such large change, no consensus has been reached on the best approach. Energy analysts and policymakers are seeking empirical research to develop strategies and aid decision-making on this global issue.

1.2 Global Approach to Tackling Climate Change

Over the past few decades, the emission of greenhouse gases has gained a much greater focus, as humanity seeks to avoid the very real and extreme consequences of climate change [2] [6, 7]. In addition to GHGs, other environmentally harmful pollutants are starting to have a more significant presence in all forms of decision making, and are being incorporated in both industry [8], and government-led planning [9, 10]. Globally, the mitigation of climate change is receiving the greatest precedence, and has been widely considered the greatest threat of our time [11, 12].

Evidence continues to mount for the more severe side-effects of global warming such as higher temperatures, changing landscapes, rising seas and drought [13].

A global response to the growing threat of climate change, resulted in the adoption of the Kyoto protocol by the United Nations Framework Convention on Climate Change (UNFCCC) in 1997; the world's first greenhouse gas emissions reduction treaty which entered into force in 2005 [14]. The Kyoto Protocol to the Convention commits its parties to binding targets based on the emissions of a 'basket' of GHGs, including carbon-dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF₆), and now as of the second period, also nitrogen trifluoride (NF₃). Reduction targets agreed by committed nations are measured in relation to 1990 emissions levels, which was set as the benchmark year for the protocol. Despite the significance of a multi country alliance in tackling this issue, the agreement only covers developed nations within the UNFCCC. At the Paris climate conference (COP21) in December 2015, a new global climate agreement was adopted by 195 countries, including developed and importantly developing nations, which is set to replace the Kyoto Protocol in 2020 [15]. It is hoped that this agreement will lead to the concerted effort required globally to avoid catastrophic climate change. The agreement sets out a global action plan to limit global warming to well below 2°C.

The UNFCCC requires all parties to submit national inventories of anthropogenic GHG emissions and sink removals [16]. Nations that have ratified the Kyoto Protocol must provide these reports annually and also include supplementary information demonstrating their compliance. Developing country parties are required to submit their first national communication within three years of entering the Convention, and every four years thereafter. National GHG inventories provide a baseline of data, to pinpoint areas of largest impact and are a means to assess progress in reaching reduction targets. Conventionally, only GHG emissions generated within a nation's own border are included in their inventory; also known as production-based emission accounting. Consequently, GHG emissions arising from the importation, or embodied within imported materials and products are not included. Critics have suggested that developed countries are simply outsourcing their more energy intensive, high carbon production activities abroad, relieving them of the responsibility for these emissions [17]. Additionally, international shipping and aviation emissions are omitted from the convention despite accounting for 5% of global GHG emissions [18, 19].

Global carbon dioxide levels broke the monthly average threshold of 400ppm for the first time in 2015, highlighting the urgency required for action [20]. Wide systemic change must now take place, particularly in the energy sector, to spur on quicker progress and to achieve deeper decarbonisation. This is particularly true in developed countries, such as the UK, where many of the easy gains have already been implemented (i.e. fuel switching from coal to gas etc.) [21]. Some early signs of progress in tackling climate change are beginning to be observed, e.g. the global domestic product (GDP) has demonstrated preliminary signals of decoupling from fossil fuels and

industry based GHG emissions [13]. However, governments have failed to deliver a long-term energy policy framework to support this transition to a low carbon future [22, 23], due to their reluctance to ‘lock-in’ to a set approach. Further guidance is required to not only ensure the best decarbonisation pathway is taken, but that it can be delivered affordably, while also maintaining security of supply. Furthermore, it’s critical that any action proposed to decarbonise the energy sector is fully investigated to ensure wider environmental burdens are kept to a minimum, in order to avoid otherwise unforeseen negative consequences.

1.3 UK Approach to Tackling Climate Change

The UK became the first nation in the world to implement a legally binding GHG reduction target through the Climate Change Act in 2008 [24]. The act commits the UK to reducing its greenhouse gas emissions by at least 80% below 1990 levels by 2050. The act injected great political impetus, resulting in the growth of many green policies to help incentivise low carbon technology investment. A system of five-yearly carbon budgets were set out to provide interim targets to safeguard sustained progress out to 2050. An independent statutory body known as the *Committee on Climate change* was also established by the act to provide independent advice to Government and Devolved Administrations on setting and meeting these carbon budgets and preparing for climate change.

A fundamental step in realising the ambitious GHG reduction target is the decarbonisation of the electricity supply. Currently, the electricity sector accounts for 122Mt CO₂e, equating to 24% of total UK GHG emissions [21]. The *Committee on Climate Change* have long advocated that early decarbonisation of the electricity sector is crucial in supporting deeper decarbonisation measures in later carbon budgets, with all GHG emissions associated with the electricity supply large eliminated by 2050 [25, 26]. Securing significant GHG emissions reductions in this sector will provide a low carbon energy source, which could then support the decarbonisation of various sectors such as transport, heat and manufacturing via increased electrification. Much of the UK’s generation capacity is nearing the end of its life [27], and significant investment in the electricity sector is therefore required, not only meet low carbon objectives, but also to ensure enough capacity is available to provide a secure supply for years to come [28]. Jointly, these factors represents a time of great opportunity for the transformation of the electricity sector. However no consensus has been reached on how best to realise such a transition which has led to significant energy policy uncertainty [29].

Energy policy in the UK is driven by three key goals; to deliver low carbon, affordable and secure energy supply; together, they are known as the ‘energy trilemma’ [28]. The focus has shifted somewhat from climate change, in favour of cost and security of supply over the past few years. This shift has been induced by the economic recession, rising energy prices and a reducing capacity reserve margin [29]. Renewable energy subsidies have been cut in the wake of this shift through the reversal of a series of ‘green’ policy interventions [23]. For example, all onshore wind

subsidies have been scrapped, and the climate change levy exemption was lifted for renewable energy electricity generators. Accordingly, investor confidence in the sector has been damaged, and as a result, the growth of renewables is set to slow over the next five years [22, 23]. Nonetheless, the UK government remains committed to its targets, and is currently developing legislation for the fifth carbon budget [30].

Irrespective of how these key energy policy goals are finally balanced, wide systemic changes will take place within the electricity sector. A transition of this magnitude will see the energy and environmental implications of the electricity sector alter significantly. Trade-offs will be made, not only between direct emissions, cost, and security of supply, but also with wider environmental concerns which aren't given the same precedence as climate change. Furthermore, all upstream environmental burdens occurring abroad are completely unaccounted for in GHG inventories, as they are currently restricted to territorial boundaries. Research in this thesis systematically evaluates the environmental trade-offs that may occur over the course of a power system transition. The collective findings of this research portfolio provide clear scientific guidance to policymakers and energy industry stakeholders in limiting the energy and environmental implications of a transforming electricity sector, particularly its impact on climate change.

1.4 Energy Scenarios and the Transitions Pathways

Energy scenarios have been employed by nations across the world, as part of their long-term strategic thinking, to provide critical evidence to guide and support companies and policymaking [31]. The future of an energy system is very difficult to predict or forecast, requiring the consideration of many complexities, uncertainties, and unknowns; particularly as the time horizon expands. Energy scenarios allow several plausible future energy systems to be explored and compared, providing comprehensive insight into their development and implications which can improve decision-making for an uncertain or undetermined future [32]. They have been widely used to investigate potential decarbonisation routes for energy systems which could meet climate change targets.

A wide range of stakeholders across the energy arena employ energy scenarios to explore the uncertainties associated with a dynamic complex energy system under transformation. Energy scenario exercises have been developed by academics [33-36], governmental departments [37], independent statutory body [38], system operators [39] and energy companies [40]. Similar examples can be seen internationally, particularly in developed countries such as France, Germany, Finland and Canada [31], but also in developing countries such as India [41]. Globally, the most notable scenario exercise is the climate change scenarios developed by the Intergovernmental Panel on Climate Change IPCC [2, 6].

A strategic partnership between the UK *Engineering and Physical Sciences Research Council* (EPSRC) and *E.ON UK* (the utilities company) established a consortium of nine university partners to examine the role of electricity within the context of 'Transition Pathways to a Low Carbon

Economy'. This multi-disciplinary team consists of engineers, social scientists, policy analysts and innovation specialists. They developed and defined three 'transition pathways' towards a UK low carbon electricity system[42, 43], in order to understand the changing roles of large and small 'actors' in the dynamics of these transitions, and to learn from the successes and failures of past transitions. The pathways were not developed as predictions or roadmaps; rather they are a way of imaginatively exploring future possibilities, to inform proactive and protective decision making, and to enhance the potential for building consensus towards common goals.

The *Transition Pathways* project focuses on the uncertainties around governance patterns and the choices of actors, distinguishing its approach from other UK based scenario exercises [42]. In contrast, the majority of energy scenario research concentrates on the uncertainties relating to the technological feasibility of different futures. The assessment of respective costs and benefits, often rely on modelling techniques which assume actors' choices are largely driven by economic factors [44]. This approach brings its own merits but fails to determine potential system change in response to dynamic interactions between a range of actors with different perspectives and goals. These actors' choices will likely have a large bearing on the trajectory to a low carbon future [42]. Deeper understanding of these potential interactions is required in order to develop better policy strategies and instruments.

The pathways were evaluated by the consortium, assessing the technical, environmental, economic and social implications of the alternative transition pathways to a UK low carbon electricity future. The research presented in this thesis represents the 'environmental' component of the wider sustainability appraisal of these UK power system transitions and their associated technologies. The three transition pathways developed and assessed were driven by different governance logics concerning the UK power sector; specifically 'market', 'central government', and 'civil society' framings respectively. The market-dominated pathway, known as *Market Rules*, is the pathway that most reflects the current UK situation. In this pathway, the interplay of competition within a national policy framework decides the trajectory of this energy future. The *Central Coordination* pathway is the government-led narrative, where the state is heavily engaged in delivering a low carbon transition. Lastly, the Thousand Flowers pathway, which is civic-led, envisions a greater role for civil society within the energy sector to deliver a highly distributed energy system, by means of bottom-up solutions. The main characteristics of these pathways are summarised in Table 1.

Table 1. Overview of main features of the Transitions pathways: adapted from Foxon [42]

	Market Rules (MR)	Central Coordination (CC)	Thousand flowers (TF)
Governance	Market logic	Government logic	Civil society logic
Key technologies	Coal and gas CCS; Nuclear power ; offshore wind	Nuclear power; Coal and gas CCS; offshore wind	PV; Onshore & Offshore Wind; renewable Combined heat & power (CHP)
Key trends	Limited interference in market arrangements; high level policy targets and high carbon price	Central government & Strategic Energy Agency commission tranches of low-carbon generation from big companies to reduce risk of low carbon investment	Local, bottom-up diverse solutions led by local communities & NGOs, Move to ESCO business model, greater community ownership and more engagement of end-user
Key actors	Large energy companies dominate; few new entrants	Central government through the Strategic Energy Agency and large energy companies	Local communities & NGOs, ESCOs and prosumers
Key infrastructure	Grid reinforcement; 80% of generation linked to HV network by 2050	Grid reinforcement; 80% of generation linked to HV network by 2050	Establishment of smart grids, 50% of generation linked to distribution network by 2050
Electricity Demand	Increased demand for heating and transport Overall demand in 2050 (580TWh) much greater than today	Increased demand for heating and transport, but energy efficiency improvements help it reduce. Overall demand in 2050 (469TWh) slightly higher than today	Overall demand in 2050 (362TWh) lower than today, despite similar levels of electrification of transport. Heat mainly provided by renewable CHP. High rate of energy efficiency improvements and more aware consumers

The Transition Pathways consortium developed their own conceptual and analytical framework for exploring energy transition pathways, based on quantitative and qualitative methods, encompassing engineering, economic, environmental, policy and behavioural sciences [45]. Its primary basis was the multi-level perspective (MLP) for analysing the dynamics of transitions in

socio-technical systems, originally devised by Dutch researchers [46, 47]. This approach was enriched by related thinking on technological innovation systems, and work on a co-evolutionary framework for analysing low-carbon transitions [44]. This research combines technical, social and historical analysis, and thus offers insights into past and current transitions, using an analytical framework based on interactions between three levels (See figure 1):

- **The landscape** (macro level) represents the broader political, social and cultural values and institutions of society;
- **The socio-technical regime** (meso level) reflects the prevailing set of practices that actors and institutions use and that developed and underpins a particular technological system;
- and **niches** (micro level) represent spaces that are at least partially insulated from ‘normal’ market selection in the regime that provide places for technological and social learning to occur.

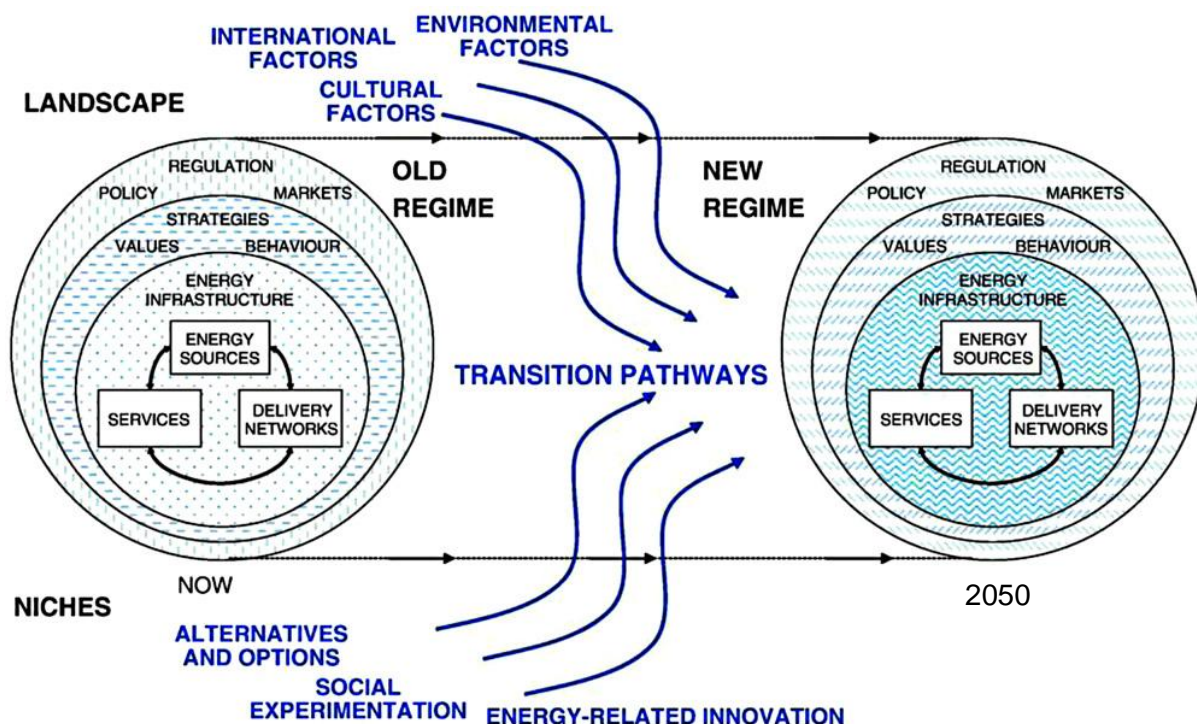


Figure 1. Possible Transition pathways and the factors influencing them; adapted from Foxon et al.[48]

The consortium defined three core transition pathways for the UK moving to a low carbon electricity system, with each pathway dominated by its own governance logics. The initial narratives (or storylines) for the pathways were founded on a range of important research outputs; a critical review of UK and international energy scenarios and approaches to scenario building [32], workshops with stakeholders from policy, energy companies and non-governmental organisations, and finally, a set of interviews with energy system ‘gatekeepers’[49].

A three-step process was employed in identifying the initial outline of the transition pathways:

- (1) Characterising the existing energy regime, the internal tensions and landscape pressures;

(2) Identifying dynamic processes at the niche level; and

(3) Specifying interactions giving rise to, or strongly influencing, transition pathways.

These three steps were applied iteratively to develop greater depth of detail of the characteristics, processes and interactions which constituted each pathway. Quantification of the pathways was then carried out by an interdisciplinary team to produce version 1.1. This team comprised of consortium members with a deep understanding of energy service demands, generation technologies and the delivery of electricity to consumer based on wider theoretical and applied research experience [50]. Quantification was an iterative process, which firstly required the change in demand for services consuming electricity to be specified based on the narrative. Then the change in power generation mix was established, in line with the governance logic and actors' choices, for each respective pathway. The elaboration of the narratives and their corresponding numerical representations were further enhanced following the interrogation of the initial pathways. The pathways were fully investigated using a combination of empirical quantitative modelling, qualitative analysis, and a series of further stakeholder workshops. This led to the re-elaboration of the pathways, resulting in two more iterations; version 2 and 3 of the pathways. A full account of the approach taken in the re-elaboration of the pathways can be found in Article IV of this thesis.

The electricity generation portfolios for the latest pathway (version 3.2) are presented here in Figure 2-4, projecting the technological trajectory of each transition out to 2050.

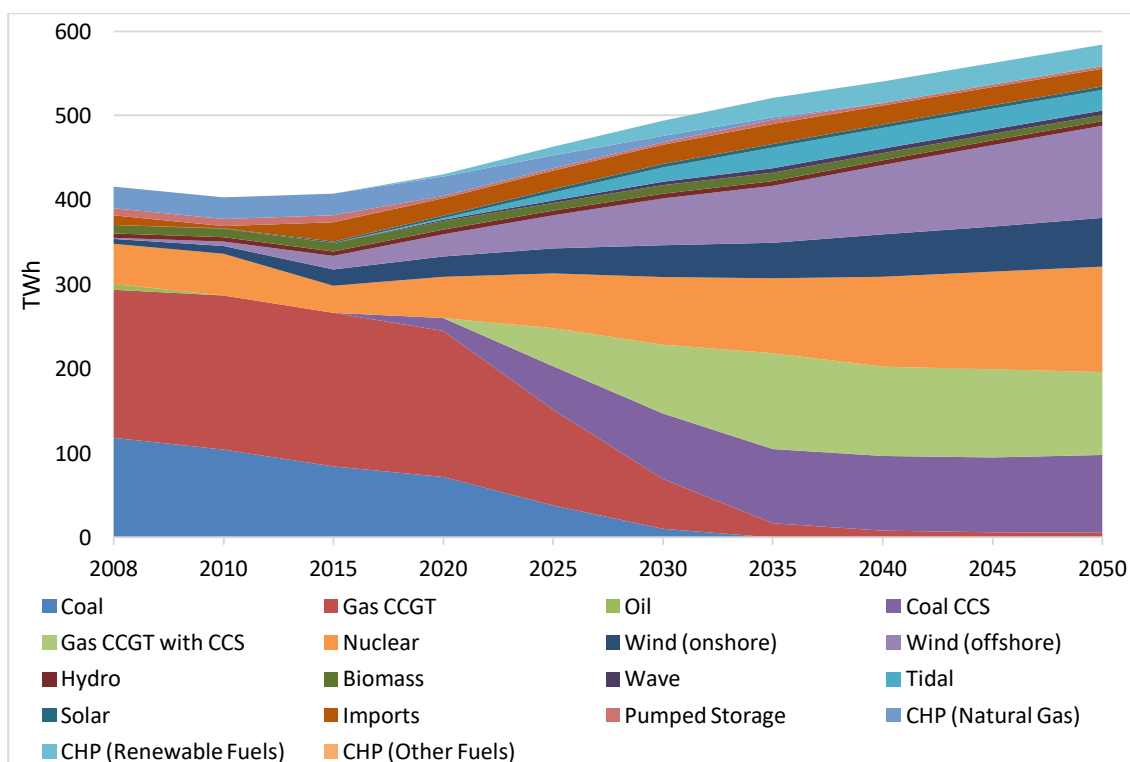


Figure 2. Electricity generation portfolio for Market Rules pathway

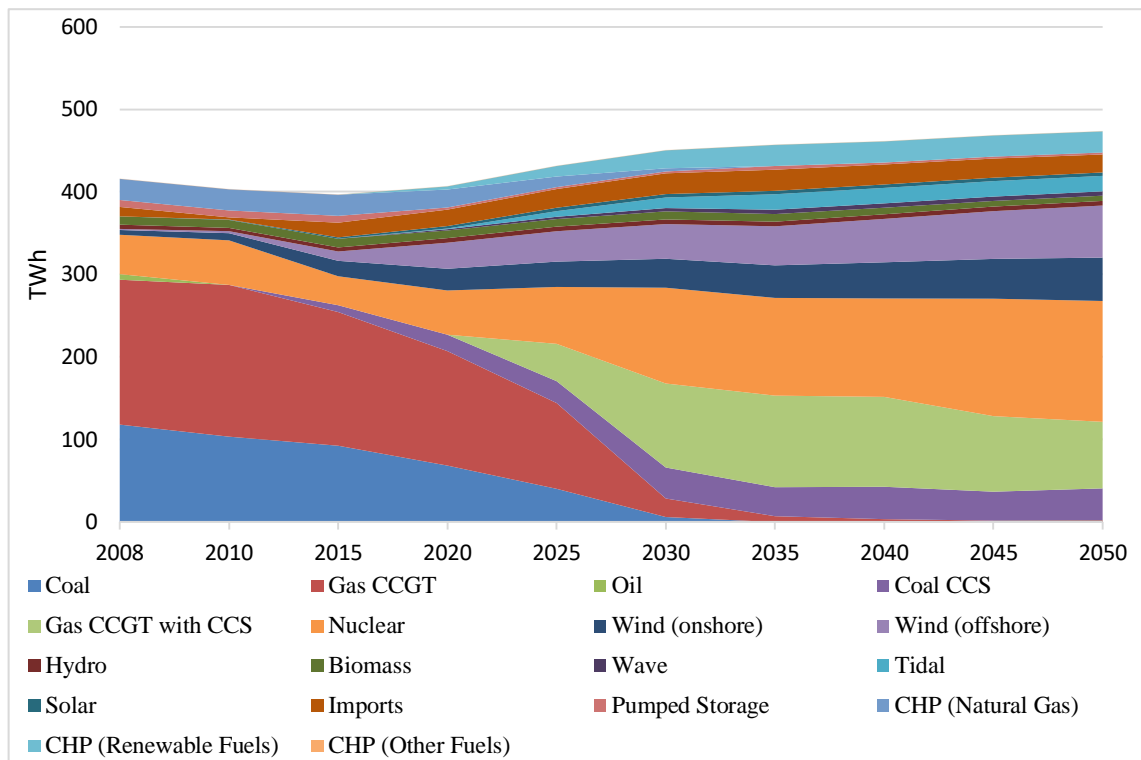


Figure 3. Electricity generation portfolio for Central Coordination pathway

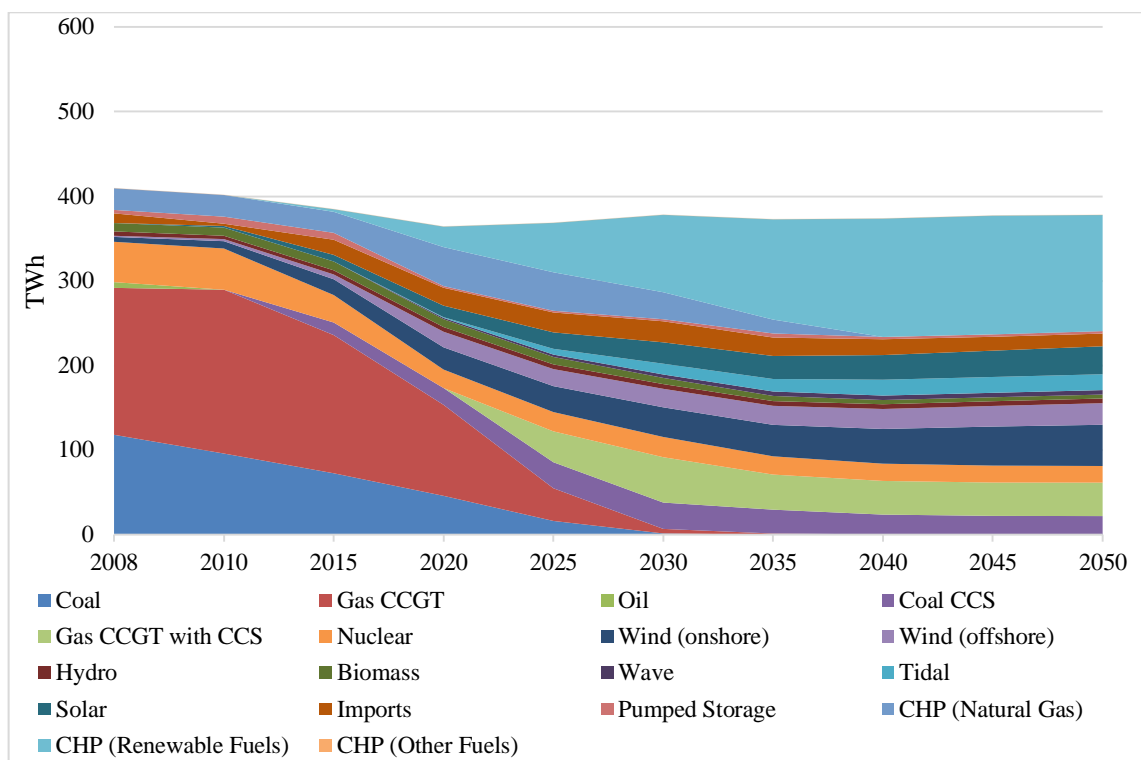


Figure 4. Electricity generation portfolio for Thousand Flowers pathway

1.5 Scope of Research

Key drivers of UK energy policy are to deliver a low carbon (on a ‘direct’ basis), affordable and secure energy supply. Thus, policies which are currently being developed to direct the future of the electricity system don’t adequately account for any non-direct GHG emissions, or other wider environmental impacts. The focus of this research is to investigate the energy and environmental implications of low carbon transitions for the UK power sector out to 2050, and their associated technologies. Life cycle assessment and related methods, such as carbon footprinting and energy analysis, were used to assess the environmental performance of these future electricity systems. These methods and the research approach taken have been discussed in greater detail in chapter 2. The portfolio of research presented in this thesis, provides scientific evidence to inform proactive decision-making by policymakers and other energy stakeholders on these wider energy and environmental impacts. Seven academic works were selected to meet the aim and corresponding objectives of this thesis as set out in the following section.

1.6 Research Aim and Objectives

The primary aim of the work reported in this thesis was:

To assess the energy and environmental impacts of the UK electricity system, and its associated technologies, as it transitions towards a low carbon future.

In order to meet this aim, the following six objectives were accomplished, through the portfolio of works presented in this thesis, as outlined below:

Objective 1. To perform a critical review of the life cycle assessment methodology as applied to the evaluation of energy systems

Objective 2. To determine the life cycle energy, greenhouse gas (GHG) and environmental impacts of the development of a more electric UK power sector.

Objective 3. To highlight the environmental significance of ‘upstream emissions’, along with their technological and policy implications.

Objective 4. To explore how multidisciplinary and interdisciplinary modelling approaches can inform the future development of the UK power system within a decarbonisation framework.

Objective 5. To examine the environmental impacts of new entrant electricity generators options which may be adopted, and their role in the decarbonisation of the UK electricity sector.

Objective 6. To identify areas of considerable systemic change for the future UK power system, and quantify their impact on the environmental performance of future UK electricity.

2 Methods and Research Approach

Three interrelated environmental management tools were used to evaluate the energy and environmental performance of electricity systems in this research portfolio. They were Life Cycle Assessment, Carbon Footprinting and Energy Analysis. The chapter lays out the tools and key and methodological principles, justification of use, and finally the research approach employed when using these methods in this thesis.

2.1 Life Cycle Assessment

2.1.1 *Application of LCA to energy systems*

The main source of environmental impacts associated with an electricity generator is very technology dependent. Many conventional electricity generators rely on the combustion of fossil fuels for energy, which produces a large quantity of direct emissions, accounting for much of their associated environmental burden. Although alternative electricity generators may not produce such emissions directly, they often rely on more material-intensive technologies (e.g. wind and photovoltaic PV), or may require a large new infrastructure (e.g. tidal barrages). These activities results in the release of emissions indirectly, and come with various other environmental consequences. Therefore, to truly assess the environmental impact of electricity, production cannot be looked at in isolation, but must be considered along with all other related processes and the summation of their impacts. Hence, ideally such analysis should be carried out on a life cycle basis in order to capture the ‘true’ environmental profile of a particular electricity generator. Life Cycle Assessment (LCA) has been designed exactly for this type of comprehensive assessment [5].

LCA is the most established and developed tool to evaluate the environmental impact of a system [51]. All flows related to a given product or service was examined, encompassing its entire life cycle, scrutinising each process from the acquisition of raw material, production, use and disposal. A wide set of predetermined environmental categories are assessed encompassing all life cycle stages, providing a full account of the environmental performance of a system; potentially circumventing problem-shifting [52]. LCA’s holistic approach makes it particularly suitable for the assessment of electricity systems, since many alternative electricity systems show little impact directly, but may have significant impacts upstream [53]. It also provides a well-established and comprehensive framework [54, 55] to facilitate robust comparisons between different electricity systems which could be used to inform policy. Accordingly, LCA was the clear choice of environmental management tool for this research, providing a comprehensive environmental assessment of alternative electricity systems which could be systematically compared. A fuller description of LCA methodology, as codified in the ISO 14040 standards series [54, 55], can be found in article I of this thesis.

LCA is a comprehensive tool for determining the regional and global impacts of a system, but does not account for localised impacts or the sensitivity of the receiving environment [56, 57]. Therefore, LCA must be combined with other environmental management tool such as Environmental Impact Assessment and Risk Assessment to provide a full account of the potential environmental damage of an energy system. However, these assessments would need to be carried out on a case by case basis, with specific knowledge of the local environment. The integrity of an LCA is heavily dependent on the quality and availability of its input data. For more novel or emergent energy technologies, obtaining data that accurately reflects the energy system being assessed can prove challenging; particularly if these systems incorporate novel materials or processes [58]. Although LCA has a full established framework, technical assumption and value choices are required at various stages [56, 59]. The assumptions adopted in a LCA regarding system boundaries, allocation methods, and end of life treatment, could result in large variation in overall results. Hence, it is critical that all subjective choices are aligned between studies before a fair comparison can be conducted [55]. This inherent variability and uncertainty in LCA needs to be captured and understood by stakeholders when using LCA results to inform decision-making. A fuller exploration of LCA limitations is provided in article I of this thesis.

2.1.2 Evolution of LCA

LCA was originally developed in the 1960's as a resource management tool [60]. Early studies focused primarily on energy efficiency, the consumption of raw materials and waste disposal [61]. By the early 1990's, LCA was recognised as one of the most promising tools for assessing a wider range of environmental issues [61]. Shortly afterwards the first standards were developed by the Society of Environmental Toxicology and Chemistry [62] [63]. At this juncture, interest in LCA greatly broadened, and it began to be incorporated in regulatory processes. Since this time, LCA has become an extensively applied and wide ranging environmental tool across industry, policy and academia [60].

LCA was first developed to assess a single product life cycle, however, there has been a clear move to utilise the tool to inform larger scale decisions. This has led to the expansion of LCA into two forms; the traditional LCA known as attributional LCA (ALCA), and consequential LCA (CLCA). The differences between these two forms of LCA are largely the results of choices made during the goal and scope stage, dependent on the type of research question the study is trying to address [64]. An attributional approach accounts for all the environmentally relevant physical flows to and from a product or system, and its associated processes. A consequential approach on the other hand aims to assess how environmentally relevant flows will change in response to different potential decisions [65].

Both consequential and attributional methodologies of LCA provide valuable policy support and can be applied when modelling future systems [66]. Attributional LCA provides a broad overview

of the environmental consequences of a future system, whereas consequential LCA provides insight into the influences of decision makers, and the nature of a product chain on future systems. The insights provided by both methodologies are invaluable as policy makers and regulators attempt to address multiple environmental goals. Together, they can provide a more rounded environmental assessment within a wider socio-techno-economic assessment framework [42].

Both modelling approaches rely on a simplified model of reality. Therefore, it's not a matter of which approach is best, but rather which approach can provide the insights required, and whether it is a plausible or implausible model for the given question and available data[67]. Outputs from each approach can inform and guide policy-makers and other stakeholders when investing in new generation technologies and considering their GHG performance as part of the energy policy 'trilemma'[48], i.e., the simultaneous delivery of low carbon, secure, and affordable energy services. Hence, both approaches provide value in meeting the objectives of this thesis set out in section 1.6.

Despite interest widening and great application of LCA to account for the consequential impacts of decision-making, CLCA vary greatly between studies, with a need to develop a more systematic and consistent methodology [60, 65, 68]. In order to fully appreciate the distinction between ALCA and CLCA, an overview of some of their most fundamental differences are provided below in table 2.

Table 2. Overview of difference between ALCA and CLCA

Characteristics	Attributional LCA	Consequential LCA
Research Goals	Broad assessment of the environmental impacts of a given product or system, and its subsystems.	Consequential LCA evaluates the change in flows in respect to a given decision or market, and subsequently the corresponding change in environmental impact.
Purpose	ALCA is useful tool for emissions accounting, general technology assessment, and informing policy [60].	Since CLCA's prime focus is the change in response to a decision, therefore, it is very much a policy tool [60]. It cannot be used for emissions accounting, as system boundaries tend to be large and include boundaries of wider systems. Hence, double accounting could occur [68]
System Boundaries	All environmental relevant inputs and outputs which are associated with the resource acquisition, production, use or disposal of a product or system are included [52].	The system boundaries tend to be much broader than their ALCA counterparts. Typically the boundaries are defined to include all activities contributing to the environmental consequence of the change, which can be within or outside the life cycle of the system being investigated. Unaffected elements of the system are often then excluded [60].

Input data	ALCA uses average data that represent the actual physical flows.	Tend to rely on marginal data “when relevant to the purpose of assessing the consequences” [60, 64]. The advantage of focusing on marginal data is that it can narrow the data requirements of the study by excluding unchanged aspects [60]. However careful explanation of elements of the system which will not change is required.
Allocation	Impacts associated with multi-functional processes are partitioned based on some physical property such as mass, energy or exergy basis, or economic value [52].	Allocation between multi-functional processes is typically avoided through system expansion [69].
Complexity	Since ALCA studies are based on linear and static models, making assumptions taken easier to comprehend [64].	System complexity is higher in CLCA as they consider wider range of economic, market and social factors [65].
Uncertainty	ALCA has less associated uncertainties as it's based on linear and static models.	CLCA are more sensitive to uncertainties compared with ALCA. Depending on the complexity of the study, uncertainties can be quite high, particularly as the time horizon grows [64]. Uncertainty in the marginal data is often large [70].
Time-considerations	Excludes temporal information [56].	CLCA models change in environmental impact that occurs as a result of a decision dynamically over a chosen timeframe [68].

Both approaches were applied in this thesis in respect of the aim of the research, and the overall scope of the *Realising Transition Pathways* project. Evidently, significant variations can occur between ALCA and CLCA, and also in terms of the research question, system boundaries and other methodological choices between assessments. Accordingly, the approaches taken to meet the objectives of this thesis have been set out in the following two sections.

2.1.3 Attributional LCA approach

One of the main objectives of this thesis was to evaluate and compare the life cycle greenhouse gas (GHG) and environmental impacts of the development of the power sector for three more electrified UK futures. An attributional LCA approach was deemed most suitable, accounting for all environmentally relevant physical flows to and from the electricity system, and its associated subsystems and processes. The result was a wide environmental profile of these future electricity systems. Accordingly, an ALCA approach was employed for the majority of the environmental assessments conducted over the course of this research.

One of the most critical stages in framing a LCA is defining its goal and scope. Article II and Article VII share the same primary aims, namely to quantify the life cycle GHG emissions

associated with three transitions pathways electricity systems [*Market Rules (MR)*, *Central Coordination (CC)* and *Thousand Flowers (TF)*]. Article VII aims expanded further to also assess the wider environmental performance of these systems. Additionally, sensitivity analyses were conducted to assess the implications of a changing policy landscape on results.

The appraisals of the *transition pathways* and their associated environmental burdens were evaluated, by means of two functional units; in terms of 1kWh of electricity produced, and related to the UK total electricity demand (e.g. in TWh). The system boundaries of this assessment were defined as ‘cradle-to-gate’ electricity provision (as shown in Figure 5). The ‘cradle-to-gate’ system boundaries included all upstream processes from material extraction, manufacturing, transportation, and construction of the power plant. The downstream boundary was effectively taken as the point of electricity end-use: delivery to the home, the commercial service provider, or to the factory.

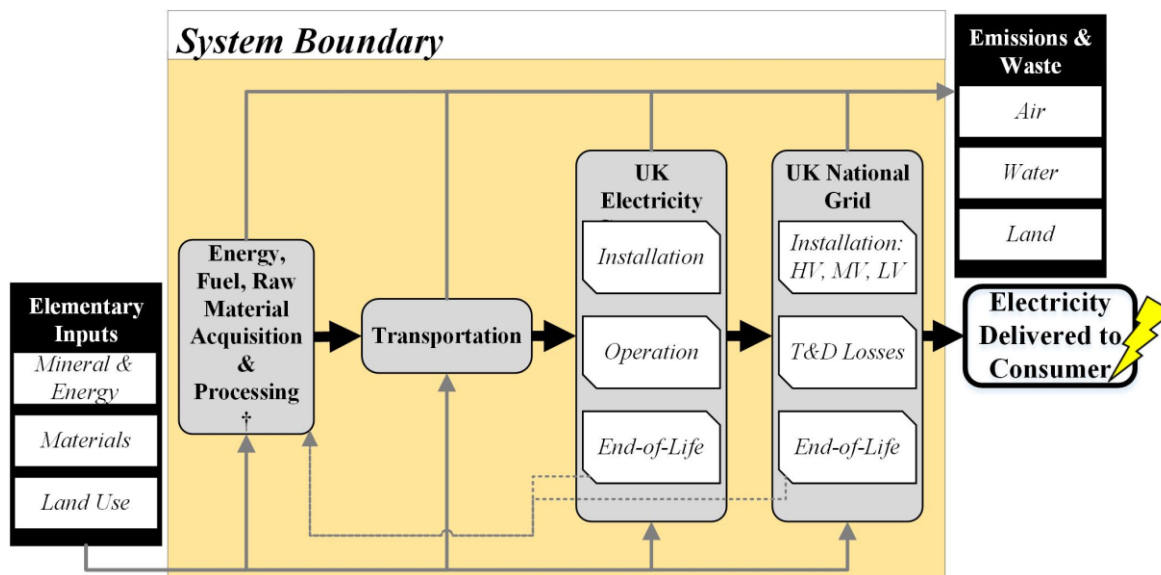


Figure 5. System boundary diagram for the life cycle assessment of UK electricity provision from ‘cradle to gate’

Every stage of the life cycle within this system boundary was systematically analysed from resource acquisition, production, through to use and disposal [71, 72]. The life cycle impacts of the UK power generators, specified in these transitions, were determined using LCA datasets from the *Ecoinvent* database (version 2.2) [73], populated with real-life data compiled from current operational power plants [74, 75]. For more novel technologies, such as tidal and wave, proxy datasets were developed in accordance with studies of these technologies [76, 77]. The coal and gas-fired generation datasets were adapted to account for the impact of *carbon capture* facilities, based on detailed studies of these technologies [78]. It was assumed that 90% of direct emissions were captured for both technologies, although coal CCS incurred a 23% energy penalty (average of the coal technologies examined), whilst gas CCS incurred a penalty of 17%. Data on generation (both self-generation and net generation), and transmission and distribution losses, were accounted

for, based on the quantitative representation produced for each pathway (see Article IV for details). The ReCiPe life cycle impact assessment methodology was used in these assessments, employing 18 midpoint indicators, in order to account for wider environmental concerns.

The output of this research provides the ‘environmental’ component of the wider sustainability appraisal of these UK power system transitions and their associated technologies. The collective findings collated across the project’s different work streams have been developed to provide broad policy direction, and could be used to inform a variety of different decisions. Hence, the comprehensive overview provided by an attributional assessment of the environmental impact of the different electricity system was most appropriate.

Nonetheless, this approach comes with limitations. It depends on static linear models of impact, based on average supply chains, subject to spatial and temporal constraints [56, 68, 70]. Current life cycle data for different generators was used to account for future plants and uncertainties in their technological improvements; which is an inherent limitation when carrying out future-oriented research.

2.1.4 Consequential LCA approach

Wide environmental profiles of the three future electricity systems set out by the Transition Pathways were determined using ALCA. However, possible future areas of considerable systemic change could have significant bearing on these results. The UK gas supply was identified in this thesis (see article V and VI in this thesis) to be a key area which could be subject to large change in response to diminishing domestic reserves [79]. The need to examine this change more fully was further emphasised by the wide touting by both academics and policymakers, of gas as a critical bridging fuel in society’s transition to a lower carbon future [80].

There are many external pressures at play which are likely to influence the UK market over the coming years [79, 81], such as increasing Asian demand, diminishing reserves in the European Union, and growth in unconventional gas sources (such as shale gas and biomethane). The UK gas supply will depend on future contracts negotiated based on technical, political and economic factors. Ultimately, the consumed gas will be chosen based on the least expensive, most secure and viable supply chain. The implications of these potential decision-makers’ choices for the future UK gas supply were explored in Article VI. Hence a consequential approach was taken to evaluate the change in GHG performance of the future UK electricity system in response to a gas supply evolution as a result of these potential decisions. This approach was deemed most appropriate to investigate the environmental implications of these likely potential choices over time, in order to limit risk when undertaking strategic technological decision-making. Examining this type of large systemic change, along with the influx of new entrant generators, also contributed to fulfilling objective 5 and 6 of this thesis.

Given that the primary focus of this thesis is the environmental impacts of electricity, the system boundaries of this consequential life cycle approach were not expanded to evaluate the wider environmental impacts of this change. Wider consequences of the dynamics processes associated with the gas supply evolution, which are often the focus of other CLCA [68, 82] were not considered in line with the goal and scope of this assessment. Instead, the system boundaries were only expanded to include shift in demand for new sources of gas, namely, shale gas and biomethane. As such, all changes accounted for were only associated with the UK electricity system. Furthermore, tightening the focus of the consequential processes helps to reduce the overall level of uncertainties, which are typical higher in CLCAs [64]. This is an important consideration given the existing high levels of uncertainty that are intrinsically linked with scenario development [32].

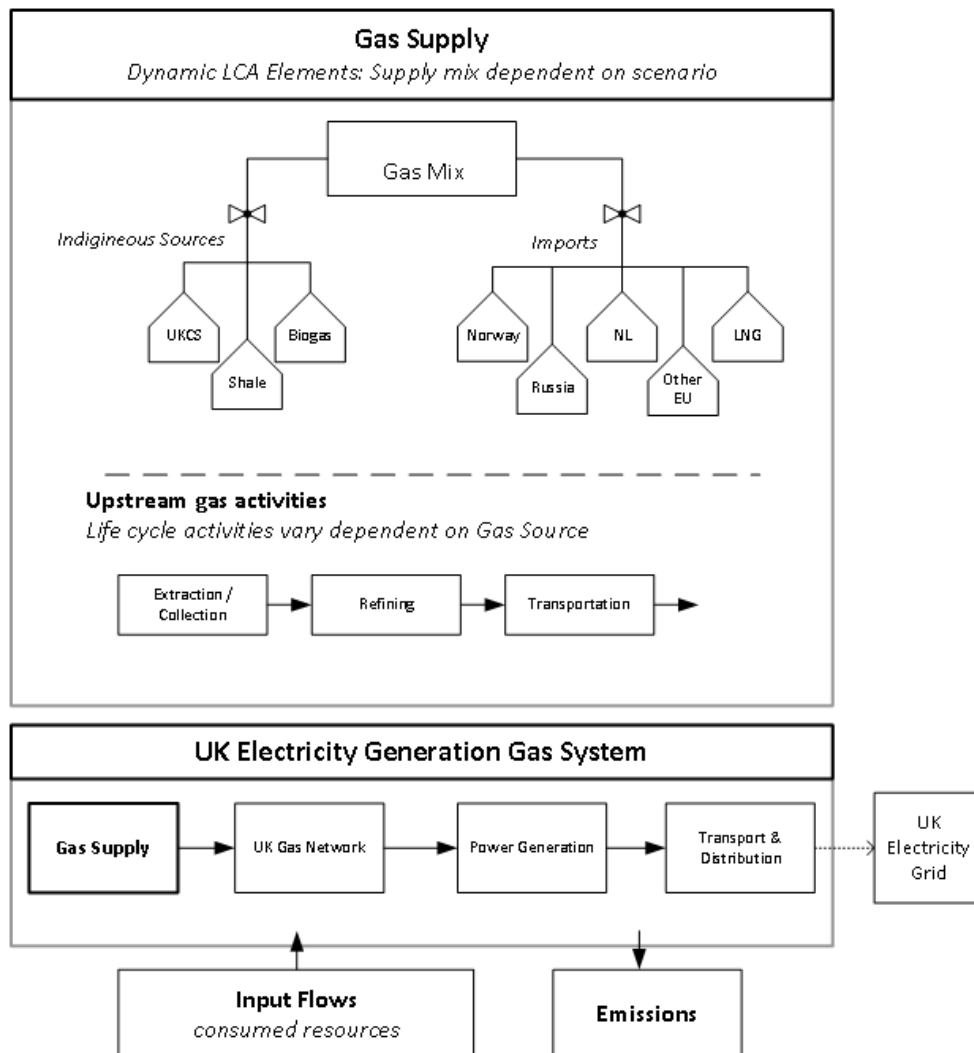


Figure 6. System boundaries of the dynamic elements of the UK electricity generation gas system

The system boundaries of this assessment were defined as ‘cradle-to-gate’ electricity provision (see Figure 6). All upstream processes were included from material extraction, manufacturing,

transportation, to the construction of the power plant. The downstream boundary was taken as the point of delivery to the electricity transmission grid. This analysis builds on the preceding attributional life cycle GHG assessment of the UK electricity system, from ‘cradle to gate’, for the three different *Transition Pathways*. In the baseline analysis (unchanged elements of the study), all data and assumptions were based on current prevailing technology, providing a static snapshot appraisal of the UK electricity system (as outlined in section 2.1.3). The functional unit in this assessment was the total UK electricity demand (e.g. in TWh), which was the basis used to compare the impact on the three transition pathways.

Three potential future gas mixes were developed to explore their impact on the future UK ESI emissions, based on projected gas trends, market developments, and future production insights, as outlined in Article VI. The three future gas mixes were paired with the three *Transitions Pathways* (in place of the 2012 gas supply mix), allowing their impact on a potential future UK ESI to be investigated through nine potential energy future scenarios. This analysis does not attempt to predict the future but rather explores the potential implications of an evolving gas supply on the GHG performance of three different UK electricity systems. This approach shares similar limitation to the attributional assessments. The gas supply datasets were based on average supply chains, subject to spatial and temporal constraints [56, 68, 70].

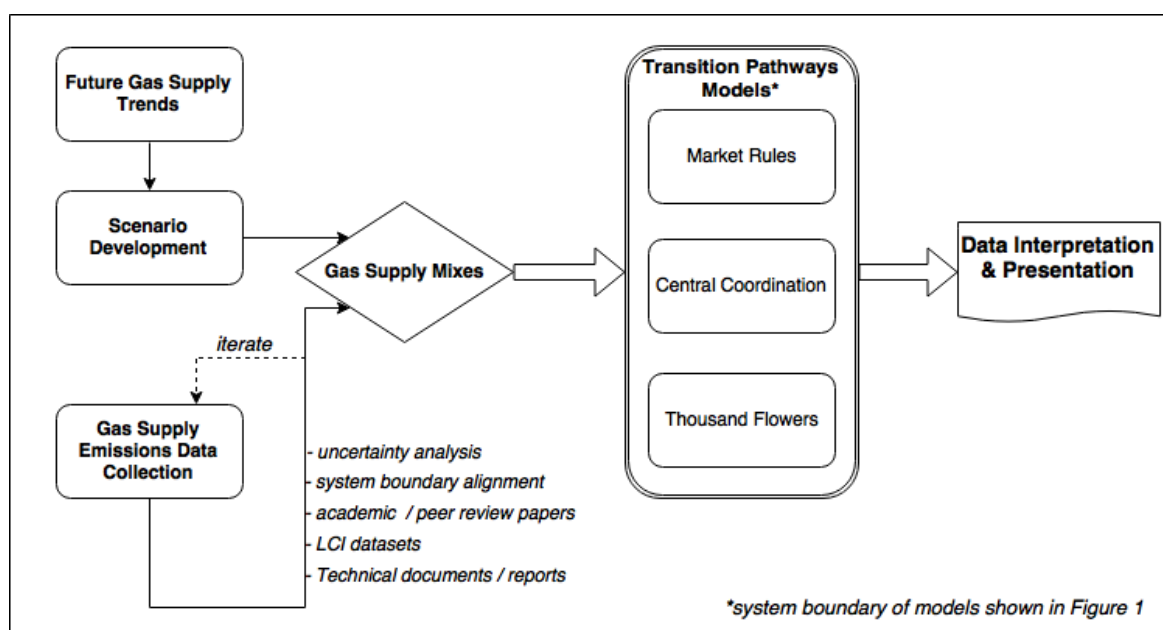


Figure 7. Figure A flowchart outlining the consequential approach adopted in Article VI

A flowchart outlining the development of the consequential approach is provided in Figure 7. Firstly, the gas supply scenarios were developed based on wide-arching technical, political and economic trends that will affect the UK gas supply out to 2050. Upstream gas supply data were collated, and each source checked and verified. These gas source emissions datasets were then

paired with the gas supply scenarios to account for the dynamic change in GHG emissions associated with the evolving gas supply out to 2050. These results were then combined with the unchanged elements of the system (i.e. all processes not upstream gas related), to determine the GHG performance of the future UK electricity system.

2.1.5 Allocation of emissions

Over the course of a system's life time, different environmental burdens will arise as a result of the diverse range of processes, from the acquisition of raw materials, to its construction and use, and finally to its disposal. Depending on the nature of the system, different life cycle stages have very different levels of emissions. For instance, material intensive technologies, such as nuclear power plants, wind and solar farms, see a large peak in their impact at the beginning of their life cycle, and again at their final disposal. In contrast, a large proportion of emissions associated with gas generation, particularly for GHG emissions occur during the use phase of its life cycle. When considering the production of electricity on a national level (as carried out in this thesis) the peaks and troughs of the different generation technologies are occurring on an ongoing basis depending on installation rates.

Two forms of emissions allocation are used in LCA to account for these impacts of a system over time, namely, steady state and dynamic (or temporal) allocation [68, 83]. Traditionally the impacts of a system or product, accounting for all of its inputs and outputs, are integrated across its life cycle, and then averaged out over its lifetime [83]. This average or steady state emissions allocation is applied in an ALCA, providing a static account of the environmental impacts for any given time. To meet the needs of CLCA, a more dynamic (temporal) approach to the allocation of these impacts is often required to track the real-time consequential impact of the assessed system in order to meet a particular research question [64, 68]. This approach accounts for the release of each emission at every given time-step throughout the life cycle. Each approach has their purpose when assessing the impacts of electricity generation depending on the research question being considered [84].

For the purposes of this thesis, steady state allocation was employed throughout all articles which were dominated by attributional approaches. A major objective of this research, and indeed its associated project, was to not only quantify life cycle GHG emissions, but also to determine the potential capability of each transition pathway on delivering long-term GHG emissions reductions. Hence, it becomes more critical to determine a benchmark of life cycle GHG impacts of a system rather than the dynamic changes in GHG which are typically considered on a reduced timeframe [64, 68]. It was asserted that not only did this allocation meet the needs of this research goal, but also limited associated uncertainty when considering three very different energy futures [70]. It is important to recognise that these pathways were developed not to provide a set road map to a low carbon future, but rather explore a 'spectrum of possibilities' [85, 86]. In essence, the environmental assessment of these pathways was not carried out to give a definitive quantification

of impact, but rather an indicative exploration of the potential environmental impact of these futures, and similar pathways. The complexity of results is also minimised for the interpretation of non LCA specialists [65] (who are the target audience of this research) by using the more conventional allocation [52, 56]. In the case of the contribution approach taken in article VI, steady state allocation was maintained to again provide a more generalised benchmark of potential consequential impact. Also, given the tight boundaries taken in this assessment, it was asserted that this type of allocation not only met the needs of the research question at hand, but also allowed the result to be more readily contextualised with wider work on the pathways.

2.1.6 Life Cycle Impact Assessment methodology

All the inflows, and outflows accounted for within the system boundary of the system assessed, are converted into potential environmental impacts during the life cycle impact assessment (LCIA) phase. Large uncertainty is present in this stage as it can be difficult to determine what impact a particular inflow or outflow will eventually cause [56]. The characterisation factors are continually been updated and improved as new research advances the understanding of these environmental mechanisms [87]. Predefined LCIA methods are widely used by LCA practitioners owing to the intricacy of this conversion step. These methods can help increase the understanding of the LCA results for practitioners, and may also facilitate comparisons between studies where the same method has been applied. However, they are limited to a set group of impact categories, which may not consider all impacts that could be relevant to a system [56]; again, this may be particularly critical when assessing a novel technology [42]. The LCIA methodology ReCiPe was applied in this thesis [88], when quantifying the environmental impacts associated with an electricity system. This methodology is widely adopted and considered one of the most comprehensive LCIA methods currently available. It was developed by leading field experts [88], to provide a consistent LCIA methodology which provided environmental category indicators at both midpoint and endpoint level. It was formed by combining and harmonising, the endpoint methodology Eco-Indicator 99 [89] and CML (Centre of Environmental Science of Leiden University) midpoint methodology [57]. ReCiPe evaluates 18 midpoint indicators as summarised in Table 3, which can then be translated into 3 endpoint categories; assessing damage to human health, ecosystem diversity, and resource availability. Impacts on climate change are evaluated using the Intergovernmental Panel on Climate Change (IPCC) 2007 AR4 method within the ReCiPe methodology (see Table 3). The midpoint approach was adopted in this thesis for two reasons; firstly, endpoint impact categories are less encompassing than their midpoint counterpart [56], and secondly, the environmental mechanisms in reaching the midpoint level is far better understood by science, and therefore have much lower levels of uncertainty [64].

ReCiPe allows impacts to be evaluated in respect to three different ‘cultural perspectives’ reflecting value choices on time horizon, and viewpoint on how future technology improvements may limit environmental consequences. These perspectives allow some of the subjectivity in LCA

modelling to be systematically accounted for, increasing the robustness of the methodology. However, this extra dimension adds to the complexity of LCA results, which are often considered difficult to interpret by non-specialist [90]. The *Hierarchical* perspective was chosen in this thesis, as it accounts for environmental impacts in line with general scientific consensus, taking a mean level of risk approach. The two other perspectives rest at either end of the cultural scale. The *Egalitarian* perspective takes a high level of risk, based on the precautionary principle, considering potential impacts that may not be fully validated by science over a long time horizon. While the *Individualist* perspective takes a low level of risk, which only accounts for undisputed impacts over a short time horizon.

Table 3. Overview of environmental impacts assessed using ReCiPe methodology

Impact Category	Midpoint indicator	Unit	Description
Climate change (IPCC 2007 AR4)	Global warming potential	kg CO₂ eq.	Climate change refers to the change in global temperature caused by the greenhouse effect by the release of ‘greenhouse gases’. The reference unit is carbon dioxide equivalent.
Ozone depletion	Stratospheric ozone concentration	kg CFC-11 eq.	Ozone-depleting gases cause damage to stratospheric ozone or the ‘ozone layer’. The reference unit is kilograms of chlorofluorocarbon-11 (CFC-11) equivalent.
Human toxicity	Hazard-weighted dose	kg 1,4-DB eq.	The emission of some substances (such as heavy metals) can have impacts on human health. Assessments of toxicity are based on tolerable concentrations in air, water, air quality guidelines, tolerable daily intake and acceptable daily intake for human toxicity. The reference unit is kilograms of 1,4-dichlorobenzene (1,4-DB) equivalent.
Photochemical oxidant formation	Photochemical ozone concentration	kg NMVOC	The release of substances into the atmosphere which react with sunlight to produce low level ozone or also known as ‘summer smog’. This smog is associated with crop damage and respiratory diseases. The reference unit is kilograms of non-methane volatile organic carbon compound (NMVOC).
Particulate matter formation	PM10 intake	kg PM10 eq.	The emission of primary and secondary particles increases particulate matter (PM) formation which is damaging to human health. The reference unit is kilograms of particulate matter.
Ionising radiation	Absorbed dose	kg U235 eq.	The release of radioactive material can cause damage to human health and the environment. The reference unit is kilograms Uranium 235 equivalents.

Terrestrial acidification	Base saturation	kg SO₂ eq.	Inorganic emissions such as sulfates, nitrates, and phosphates cause atmospheric acid deposition which in turn can change the acidity of soil and result in damage to ecosystems. The reference unit is kilograms of sulphur dioxide equivalent.
Freshwater eutrophication	Phosphorous concentration	kg P eq.	The emission of some substances, such as phosphorus, nitrogen, ammonia and nitrogen oxide can result in the over-enrichment of freshwater. The reference unit is kilograms of phosphorus equivalent.
Marine eutrophication	Nitrogen concentration	kg N eq.	The emission of some substances, such as phosphorus, nitrogen, ammonia and nitrogen oxide can result in the over-enrichment of sea water. The reference unit is kilograms of nitrogen equivalent
Terrestrial ecotoxicity	Hazard-weighted concentration	kg 1,4-DB eq.	The emission of some substances, such as heavy metals, can have impacts on the terrestrial ecosystems. Assessment of toxicity has been based on maximum tolerable concentrations for ecosystems. The reference unit is kilograms of 1,4-dichlorobenzene (1,4-DB) equivalent.
Freshwater ecotoxicity	Hazard-weighted concentration	kg 1,4-DB eq.	The emission of some substances, such as heavy metals, can have impacts on the freshwater aquatic ecosystems. Assessment of toxicity has been based on maximum tolerable concentrations for ecosystems. The reference unit is kilograms of 1,4-dichlorobenzene (1,4-DB) equivalent.
Marine ecotoxicity	Hazard-weighted concentration	kg 1,4-DB eq.	The emission of some substances, such as heavy metals, can have impacts on the marine aquatic ecosystems. Assessment of toxicity has been based on maximum tolerable concentrations for ecosystems. The reference unit is kilograms of 1,4-dichlorobenzene (1,4-DB) equivalent.
Agricultural land occupation	Occupied area	m² x yr (agricultural land)	The amount of agricultural land occupied for a certain time. The reference unit is metres squared years.
Urban land occupation	Occupied area	m² x yr (urban land)	The amount of urban land occupied for a certain time. The reference unit is metres squared years.
Natural land transformation	Transformed area	m² (natural land)	The amount of natural land transformed and occupied for a certain time. The reference unit is metres squared years.
Water depletion	Water use	m³	Amount of water consumed measured. The reference unit is metres cubed of water extracted.

Metal depletion	Grade decrease	kg Fe eq	The amount of metal extracted. The reference unit is kg Iron (Fe) equivalent.
Fossil depletion	Energy content	kg oil eq	The amount of fossil fuel extracted, based on the lower heating value. The unit is kg oil equivalent.

2.2 Carbon Footprinting

Carbon footprinting, also known as *GHG accounting*, is the most prevalent environmental assessment method as a result of growing concerns over the threat of global warming. It is the most widely used and understood metric in the mainstream to assess the environmental impact of electricity systems. However, a standardisation of this method has proven difficult due to the large variance in methodologies employed by academics, corporations and the general public. This has led to somewhat misleading environmental accreditation to many products and services which only consider the direct GHG emissions. This is particularly significant in the assessment of electricity systems which have wide-ranging upstream emissions which are habitually omitted in assessments that form the basis of important policy strategy [53]. The LCA community, along with numerous international and national organisations, have been pushing for the harmonisation of carbon footprint methodology in order to formulate an international standard [62]. Nevertheless, this process has proven rather difficult with participating countries unable to reach agreement, resulting in the production of a technical specification rather than a set of standards [91]. The LCA Steering Committee of the Society of Environmental Toxicology [62] acknowledges the importance of such simplified and practical methods. However, they warn of the use of carbon footprinting in isolation which could misguide stakeholders and lead to wider environment damage [62]. The carbon footprinting methodology used in this thesis follows the same framework as LCA, acting as one branch of the much wider and more encompassing LCA (see Table 2). It was defined in this research as an assessment of the total GHG emissions that is directly and indirectly caused by an electricity system or its related processes.

Two impact assessment methods were used to evaluate the carbon footprint of electricity systems in this thesis, both IPCC 2007 AR4 [6], and its successor IPCC 2013 AR5 [92]. These methods were developed by the IPCC in their fourth and fifth assessment reports. The methods classify the potential contribution of greenhouse gas emissions to climate change, which is referred to as its Global Warming Potential (GWP). This is a quantified measure of the globally averaged radiative forcing impacts of a given GHG over a period of time. The capacity for each GHG to capture and re-radiate outgoing infrared radiation in the atmosphere vary greatly. All GHGs are compared to carbon dioxide (CO₂), chosen by the IPCC as the reference gas with a GWP equal to one. Thus, the GWP of GHGs are expressed in carbon dioxide (CO₂), equivalents. The GWP's are reported in the IPCC report for three separate time horizons: 20, 50 and 100 years respectively. The application of each timeframe is equally valid for assessing GHG's from a scientific perspective. The 100 year

horizon has been chosen for the assessment of GHG's in this research, as it's the time horizon conventionally employed in energy policy, making it easier to compare results with other studies. This time horizon also allows for the assessment of the more long term impacts of the release of GHGs, with moderate levels of uncertainty.

One of the most significant changes made by the IPCC between the AR4 and AR5 was increasing the GWP of fossil methane from 25 gCO₂eq over a 100 year time horizon to 34 gCO₂eq for biogenic methane 32, and to 36 gCO₂eq for fossil methane; this implies that it is a far more potent GHG than previously realised. GWP's are constantly being revised as increased understanding is gained of these GHG and their impact on the atmosphere. However, both methods remain relevant from a policy perspective, despite IPCC2013 AR5 reflecting the most advance thinking in climate science. The adoption of revised GWP values is a slow process, and often takes years to be implemented after publication. AR4 GWP's were only implemented at a government level in 2015[93], despite being published in 2007. This was in response to UNFCCC adoption of AR4 GWP's for the second commitment period of the Kyoto Protocol (from 2013-2020) [94]. Hence both methods have been used in this research. The method employed has been specified in each article presented in this portfolio.

2.3 Energy Analysis

Energy analysis was conducted in parallel to LCA, and accounts for the quantity of energy being consumed across the life cycle, differentiating its origin between non-renewable (e.g. fossil fuel) and renewable energy resources. Energy analysis preceded LCA, and as such, they share much of the same fundamental methodology. The *Cumulative Energy Demand* (CED) methodology developed by Frischknecht et al. [95] was employed in this research to assess energy usage. The CED of a product or system is an assessment of all direct and indirect primary energy use throughout its life cycle. Primary energy use is broken down into non-renewable and renewable resources as seen in Table 4. The methodology is an insightful tool, providing, from the ground-up, a detailed account of the quantity of energy being consumed, from where the energy originates; be it non-renewable: fossil, nuclear, biomass from primary reserves, and renewable: wind, solar, geothermal, hydro, biomass from forest, waste and agricultural sources. Process energy analysis was applied in this thesis, which is a bottom up approach, accounting for the use of primary energy across each process chain within the life cycle of electricity generation.

Traditionally, energy use and GHG intensity have been intrinsically coupled for electricity systems, as a result of their high dependence on fossil fuels, e.g. coal, oil, and gas generators. The CED of a decarbonisation pathway provides a measure of how efficiently territorial energy demands are being met. Hence, the relationship between GHG intensity and CED can be an insightful assessment of a decarbonisation pathways success over time, particularly as overall energy demand changes and level of decarbonisation increases.

Table 4. Breakdown of primary energy resources (Both non-renewable and renewable)

Non-Renewable Energy Resources	Renewable Energy Resources
<ul style="list-style-type: none"> • fossil • nuclear • biomass from primary reserves 	<ul style="list-style-type: none"> • wind • solar • geothermal • hydro • biomass from forest, waste and agricultural sources

3 Research Commentary

3.1 Introduction

The energy and environmental implications associated with electricity generators, from present day, and as part of a wider transitioning United Kingdom (UK) Electricity system, have been assessed through the selected works included in this portfolio. This research seeks to provide a better understanding of the energy and environmental consequences of a transforming electricity system in response to potential decarbonisation strategies. Three potential low carbon transitions for the UK's electricity system were evaluated out to 2050, employing Life Cycle Assessment (LCA), to quantify their 'true' environmental impact. The intricacies and dynamics of future electricity systems were also explored, investigating their potential ramifications for wider energy and climate change policies. This commentary explores seven chosen articles, demonstrating their contribution to knowledge in this field, and to the objectives set out by this thesis. For the majority of works included, authors were listed alphabetically. The candidate's contribution has been explicitly outlined for each article included in this portfolio.

3.2 Commentary Overview

Seven academic articles have been selected to meet the aim of this thesis and its corresponding objectives. The contribution of each article is discussed separately in the following chapters. These articles have been presented in order of the thesis objectives they address.

Each article was given its own distinct chapter as set out below, which follow the same overall structure. Firstly, the contribution of knowledge provided by each article to the field of research is summarised. Secondly, the contribution of the candidate to the article is explicitly stated. The article is then presented, and finally, its key outputs in respect to the thesis objectives are discussed.

Chapter 4	Article I	‘Environmental life cycle assessment (LCA) of energy systems’
Chapter 5	Article II	‘The implications of upstream emissions from the power sector’
Chapter 6	Article III	‘Linking storylines with multiple models: an interdisciplinary analysis of the UK power system transition’
Chapter 7	Article IV	‘Reconciling qualitative storylines and quantitative descriptions: an iterative approach’
Chapter 8	Article V	‘Indicative energy technology assessment of UK shale gas extraction’
Chapter 9	Article VI	‘The life cycle greenhouse gas implications of a UK gas supply transformation on a future low carbon electricity sector’
Chapter 10	Article VII	‘The potential environmental consequences of shifts in UK energy policy that impact on electricity generation’

An overview of which objective(s) are addressed by each article is provided in Figure 8.

Objective	Article						
	I	II	III	IV	V	VI	VII
1. To perform a critical review of the life cycle assessment methodology as applied to the evaluation of energy systems.							
2. To determine the life cycle energy, GHG & environmental impacts of the development of a more electric UK power sector.							
3. To highlight the environmental significance of ‘upstream emissions’, along with their technological & policy implications.							
4. To explore how multidisciplinary & interdisciplinary modelling approaches can inform the future development of the UK power system within a decarbonisation framework.							
5. To examine the environmental impacts of new entrant electricity generators options which may be adopted, & their role in the decarbonisation of the UK electricity sector.							
6. To identify areas of considerable systemic change for the future UK power system, & quantify their impact on the environmental performance of future UK electricity.							

Figure 8.Thesis objectives addressed by each article

4 Article I - ‘Environmental life cycle assessment (LCA) of energy systems’

4.1 Book chapter

G. P. Hammond, C.I. Jones and Á. O’Grady, 2015. ‘*Environmental life cycle assessment (LCA) of energy systems*’, In: Handbook of Clean Energy Systems, Vol. 6. - Sustainability of Energy Systems, Yan, J. (ed.), John Wiley and Sons, Chichester, UK, Ch. 22, pp. 3343-3368

4.2 Contribution to Research:

A critical review for the use of LCA to evaluate energy systems was performed in this book chapter. A full account of the methodology’s origins and the development of its international standards have also been discussed. The strength and weaknesses of LCA when applied to energy systems were identified to offer guidance on how results can be interpreted and best utilised by energy practitioners and policy analysts. A series of energy sector examples were explored to demonstrate the usefulness of LCA and the insightful findings it can deduce. LCA was also compared and contrasted with related approaches, such as carbon and environmental footprinting. The first objective of this thesis was fulfilled by this article, providing a review of LCA when applied to evaluating energy systems, and exploring its strengths and limitations.

4.3 The Significance and Originality of the Article

This book chapter takes the novel approach of assessing the strengths and weaknesses of LCA in the context of its suitability in evaluating energy systems. This has been achieved by critically reviewing this methodology from the perspective of energy practitioners and policy analysts; highlighting the salient points relevant to these stakeholders. LCA results have been subject to misuse by these energy stakeholders in the past (see Article V of this thesis). This piece endeavours to reduce such future incidents by highlighting the key pitfalls when using these results, and exploring them through a series of energy sector case studies.

4.4 Contribution by Candidate:

Second author (generating 40% of content)

The candidate contributed heavily to all aspects of this article but was also solely responsible for specific elements of this piece. These aspects were the strength and weakness assessment of LCA, and illustrative examples related to the national energy sector, and the comparison of LCA with environmental footprinting. The concept and drafting of these components were carried out entirely by the candidate. The candidate also contributed to other sections as required and conducted a critical revision of the total manuscript. Lastly, a final review was carried out to

appraise the manuscript as a whole, and conduct the final presentation of the text. Furthermore, the candidate also answered and addressed various reviewer comments during the publication process.

HANDBOOK OF CLEAN ENERGY SYSTEMS

	Article type	Description	Page/Word extent
<input type="checkbox"/>	Volume Introduction	Volume Introductions will provide a broad and relatively non-technical overview of the topics discussed in the volume, at a level suitable for advanced students and for researchers without a strong background in the field.	Please refer to your Contributor Agreement for your contracted page/word extent
<input checked="" type="checkbox"/>	Article	Articles should take the form of an advanced review, aimed at researchers and advanced students with a strong background in the subject.	Please refer to your Contributor Agreement for your contracted page/word extent
<input type="checkbox"/>	Case Study	A detailed example.	~5 printed pages/4000 words

Environmental Life-Cycle Assessment (LCA) of Energy Systems

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ABSTRACT

Concerns about the environmental impacts associated with consumer products led to the development of environmental life-cycle assessment (LCA) from the early 1990s, and its codification by the *International Standards Organization* (ISO). This was followed by the realisation of the consequences of other devices and systems. The need for the energy analysis and environmental appraisal of energy systems to be conducted on a life-cycle basis therefore became evident. In a full or detailed LCA, the energy and materials used and pollutants or wastes released into the environment as a consequence of an activity or service are quantified over the whole life-cycle, typically 'from cradle-to-grave'. Such studies are often geographically diverse; that is, the energy and material inputs associated with the activity may be drawn from any continent or geo-political region of the world. But they enable a wide range of key environmental consequences to be examined as part of the device or system design process. There are four main stages of LCA that follow a logical sequence of goal definition and scoping, inventory analysis,

impact assessment, and interpretation. LCA methodology is critically reviewed from a state-of-the-art perspective and illustrated using several energy sector case studies. These examples concern specific energy technologies, as well as the ‘whole systems’ appraisal of national energy sectors and transition pathways. The current strengths and weaknesses of LCA are identified for energy practitioners and policy analysts. Material has been incorporated on life-cycle embodied energy and carbon accounting and comparisons made with related approaches, such as carbon and environmental footprinting.

Keywords: Carbon accounting, embodied energy and carbon, energy analysis, environmental life-cycle assessment (LCA), environmental footprints, sustainability, energy and power technologies, energy scenarios or transition pathways, whole systems appraisal

1. INTRODUCTION

1.1 BACKGROUND

The energy analysis and environmental appraisal of energy systems ideally needs to be conducted on a life-cycle basis, i.e., embracing the full range of extraction, production, distribution, and end-of-life processes or technologies (Reap *et al.*, 2008a). This approach involves what is now known as environmental life-cycle assessment (LCA), originally under the auspices of the *Society of Environmental Toxicology and Chemistry* (SETAC) at a series of workshops in the early 1990s (SETAC, 1991), and more recently codified as *International Standards Organization* (ISO) 14040 series of standards (ISO 2006a and 2006b). The aim of an LCA study is often to identify opportunities for environmental improvement by detecting the areas with the most significant impacts. In a comprehensive, ‘full’ or ‘detailed’ LCA, the energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole life-cycle, ‘from cradle-to-grave’ (Baumann and Tillman, 2004; Vogtländer, 2010; Hammond and Jones, 2011a). There are four main stages of LCA (ISO, 2006a and 2006b) which are shown to follow a logical sequence of goal definition and scoping (outlining aims, methodology and boundary conditions), inventory analysis (data collection - determining inputs and outputs of materials, fuels, and process emissions), impact assessment (determination of the life-cycle environmental impacts for the pre-determined inventory), and recommendations for improvement. Such studies are often geographically diverse; that is, the energy and material inputs to a product may be drawn from any continent or geo-political region of the world. But they enable a wide range of key environmental consequences to be examined as part of the device or system design process.

Determination of the life-cycle of a process, product or system is invariably difficult. It requires the elementary understanding of material, energy and emission flows across a broad spectrum. This is complicated by the fact that many such contributions are apparently hidden or ‘concealed’ from view. For example, if a consumer were to estimate the full impact of its activities they would need to consider a significant number of ‘concealed’ activities. It may be considered that many consumers live in a ‘Virtual World’ in which they interact directly. This bears the bulk of their considerations. But what lies outside this world is an unavoidable and essential web of ancillary activities. The consumer is rarely exposed to such activities and as such they have little awareness of the resulting impacts. The marriage of the two worlds leads to the real, ‘Actual World’, as represented by Figure 1. In the case of driving a car, as illustrated in Figure 1, a consumer believes

that they achieve 50 miles to the gallon (mpg) fuel economy (5.65 litres per 100 km). However, this does not bear the full environmental impact. There is an entire web of ancillary activities that must be considered, which includes each process leading up to the delivery of fuel into their vehicle in a usable format and at a convenient location. Progression up the production tree would reveal such activities as fuel pumping, delivery, refining, shipping, storage, oil well operations, drilling, exploration activities. Once the impact of such activities is accounted for the actual (or 'true') fuel economy may be only 45 mpg (6.28 litres per 100 km). In reality the consumer may have only a modest direct influence on such ancillary activities. But were they to start considering them from a consequential point of view, then they might exhibit wider environmental concern than just taking into account the burden of their virtual world (i.e., their own interactions). Thus, they may become impelled to think not only about conserving energy, but conserving all that they undertake and consume.

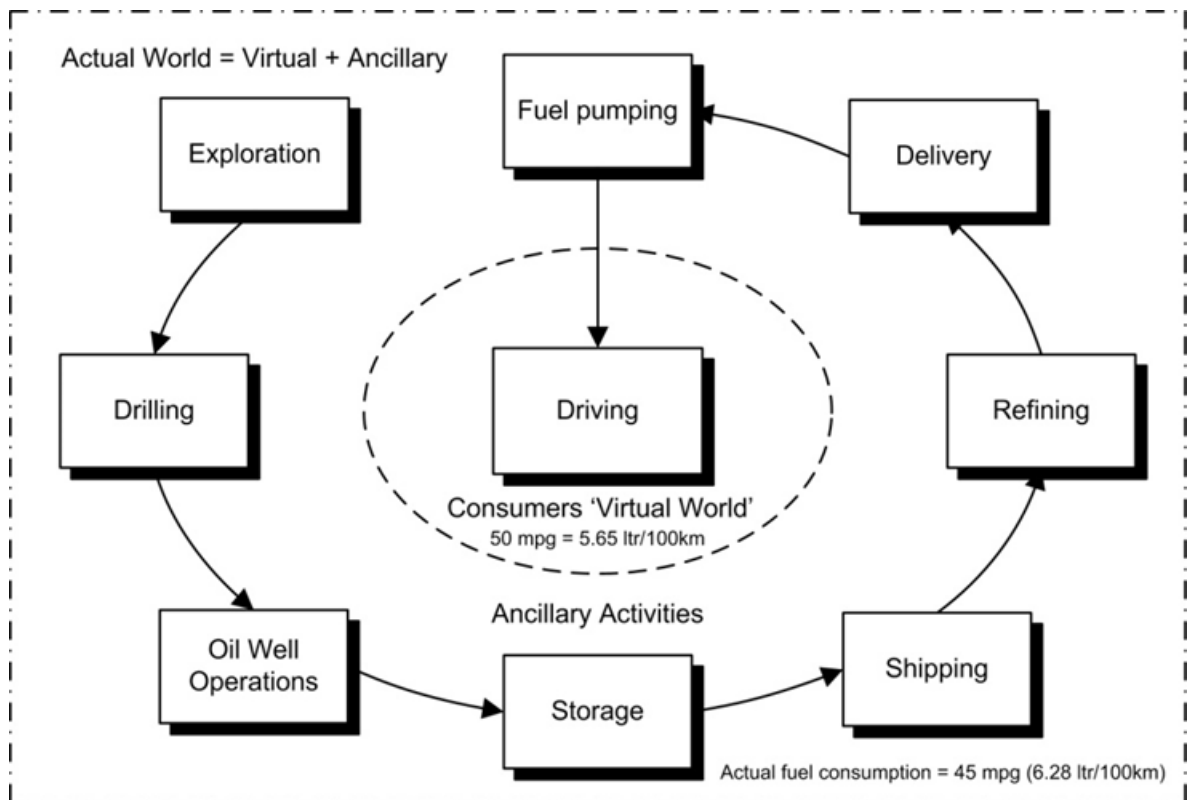


Figure 1. Life-cycle thinking: Consumers 'Virtual World' versus the 'Actual World'. [Source: Adapted from: Hammond and Jones, 2007].

1.2 THE ISSUES CONSIDERED

The present contribution is part of an ongoing research effort aimed at evaluating and optimising the performance of various sustainable energy systems (Allen *et al.*, 2008; Allen, Hammond, and McManus, 2008; El-Fadel *et al.*, 2010; Hammond, 2011; Hammond *et al.*, 2011; Hammond, Ondo Akwe and Williams, 2011) in the context of transition pathways to a low carbon future (Alderson, Cranston and Hammond, 2012; Foxon, Hammond and Pearson, 2010; Hammond and Pearson, 2013; Hammond, Howard and Jones, 2013; Hammond and O'Grady, 2014). The present state-of-the-art of LCA methodology is critically reviewed here, and its use illustrated via a series of energy

sector examples and case studies. These include specific technologies, such as biofuels and micro-generators, as well as the 'whole systems' evaluation of national energy sectors and transition pathways. This is undertaken in the context of the need to make sustainability appraisals of energy systems. The review seeks to indicate the current strengths and weaknesses of LCA with energy practitioners and policy analysts in mind as the target audience. Embodied energy and carbon accounting is discussed, drawing on the related work concerned with the authors' LCA-linked development of their '*Inventory of Carbon and Energy*' (ICE) database (Hammond and Jones, 2008 and 2011a) that has been widely used by academic researchers and industrialists. Likewise, comparisons will be drawn with related approaches, such as carbon and environmental footprinting (Hammond, 2006; Eaton, Hammond and Laurie, 2007; Cranston and Hammond, 2010; Alderson, Cranston and Hammond, 2012; Hammond and Seth, 2013).

2. THE SUSTAINABILITY CONTEXT

Sustainability was the focus of the 2002 World Summit on Sustainable Development in Johannesburg (Hammond and Jones, 2011b), where the strapline of "people, planet, prosperity" was adopted to reflect the requirement that sustainable development implies the balancing of economic and social development with environmental protection: the 'Three Pillars' model (Hammond, 2006). The interconnections between these pillars are illustrated by the sustainability Venn diagram shown in Figure 2 [Hammond (2004); adapted from a version originally developed by Clift (1995) and extended by Parkin (2000)]. Sustainability is reflected in the central portion of the diagram, where the three types of constraints are met. The originators themselves recognised that this is a simplified model (see, for example, Azapagic, Perdan and Clift, 2004). Recently the United Kingdom (UK) Government has added two additional principles of sustainable development to the three pillars (Defra, 2005): (i) promoting good governance, and using sound science responsibly [i.e., adopting 'evidence-based' approaches (Ness *et al.*, 2007)]. In the long term, Planet Earth will impose its own constraints on the use of its physical resources and on the absorption of contaminants, whilst the 'laws' of the natural sciences [including, for example, those of thermodynamics (Hammond, 2004)] and human creativity will limit the potential for new technological developments.

Parkin (2000) and Porritt (2000) have stressed that sustainable development is only a process or journey towards a destination, which is 'sustainability'. The end-game cannot easily be defined from a scientific perspective, although Porritt (2000) argues that the attainment of sustainability can be measured against a set of four 'system conditions'. He draws these from 'The Natural Step' (TNS); an initiative by the Swedish cancer specialist, Karl-Henrick Robèrt (see, for example, Broman, Holmberg, and Robèrt, 2000). Its system conditions put severe constraints on economic development, and may be viewed (Hammond, 2004) as being impractical or 'utopian'. One of them, for example, suggests that finite materials (including fossil fuels) should not be extracted at a faster rate than they can be re-deposited in the Earth's crust on geological timescales. Further confusion about this modern paradigm is added by the large number of formal definitions for sustainable development that can be found in the literature. Parkin (2000) refers to more than two hundred.

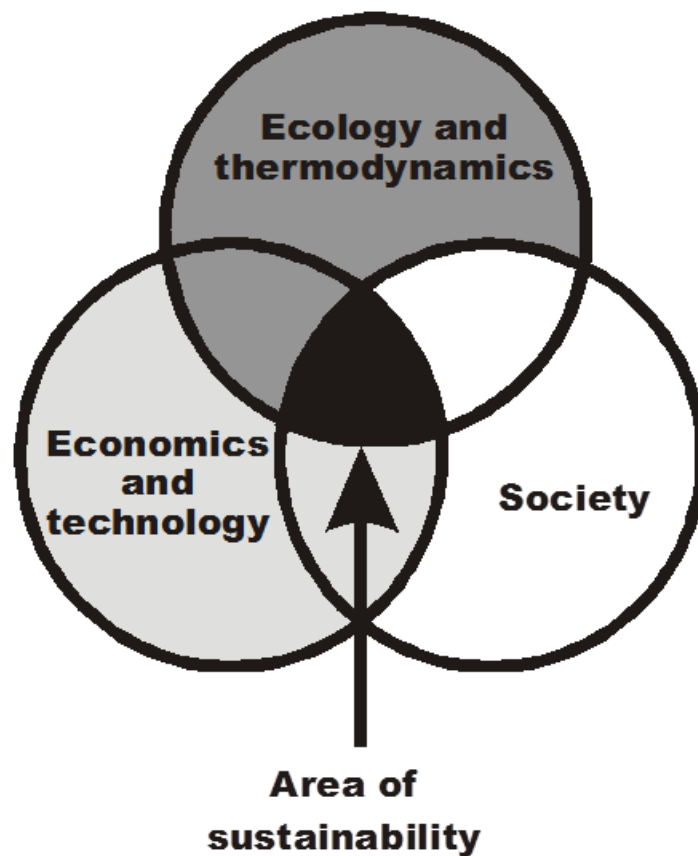


Figure 2. Venn diagram representation of ‘The Three Pillars’ of sustainability. [Source: Hammond, 2004; adapted from Clift, 1995 and Parkin, 2000].

The ‘three pillars’ of sustainability (see again Figure 2 above) imply that differing professional disciplines and insights are required in order to address each dimension (Hammond and Jones, 2011b):

- **The Environmental Pillar:** This can be tackled in quantitative terms via energy and environmental performance appraisal (see, for example, Hammond and Winnett, 2006); typically on a life-cycle or ‘full fuel cycle’ basis. These can be undertaken using the techniques of thermodynamic (energy and exergy) analysis and environmental life-cycle assessment (LCA): the main topic of the present work. They are outlined in more detail below. Typically the uncertainty band in the resulting estimates of energy system performance parameters are of the order of perhaps $\pm 20\%$ (Hammond and Jones, 2011b).
- **The Economic Pillar:** This is once more a pillar that can be addressed in quantitative terms via methods such as environmental cost-benefit analysis (CBA). However, Hammond and Winnett (2006) found that estimates of environmental costs and benefits associated with energy technologies exhibited a wide variation. These were found to reflect variations of several orders-of-magnitude variations, i.e., factors of ten. They consequently argued that this demonstrated the frailty of the present generation of monetary valuation methods.
- **The Social Pillar:** Here the approaches that can be applied are essentially qualitative. They include analytic and deliberative processes (e.g., stakeholder engagement), the mapping of socio-technical systems, customer surveys [in response to new technologies (such as smart meters) and

business models], and the ethical reflection on energy system impacts and futures (Hammond and Jones, 2011b). Clift (2007) observes that this pillar should encompass inter- and intra-generational equity concerns.

Attempts have been made to bring the above perspectives together using a variety of approaches, including a simple sustainability checklist, 'ecological' or environmental footprinting [see, for example, Chambers, Simmons and M. Wackernagel, 2000; Eaton, Hammond and Laurie, 2007; Hammond, 2006; Cranston and Hammond, 2010], multi-criteria decision analysis (MCDA; Elghali *et al.*, 2007), sustainability maps or 'tortilla' diagrams, and a sustainability appraisal framework (as advocated by the UK sustainability NGO *Forum for the Future*; founded by Sara Parkin and Jonathan Porritt). The participatory multi-criteria mapping and decision-conferencing approach developed by Elghali *et al.* (2007) for the sustainability assessment of bioenergy systems is perhaps the most comprehensive thus far devised. They drew on the lessons from modern *operational research* methods and aim to integrate these with the use of LCA (ISO, 2006a and 2006b). Elghali *et al.* (2007) produced a framework for future use, but didn't actually apply it to a specific bioenergy route. MCDA typically aggregates various distinct impacts arising from alternative technological options. Thus, Allen *et al.* (2008) argued that there are a number of reasons for discouraging such aggregate methods (including, amongst them, CBA). Decision-makers are presented with a single, aggregate decision criterion, which actually hides many disparate environmental impacts. Allen *et al.* (2008) suggest that it is vitally important that the implications of these impacts are faced, particularly by politicians, rather than obscured by the methodology.

3. HISTORICAL DEVELOPMENT OF LIFE-CYCLE ENERGY AND ENVIRONMENTAL APPRAISAL

3.1 ENERGY ANALYSIS

In order to determine the primary energy inputs needed to produce a given artefact or service, it is necessary to trace the flow of energy through the relevant industrial sector (Hammond and Jones, 2008). This is based on the First Law of Thermodynamics (the principle of conservation of energy) or the notion of an energy balance applied to the system. The upstream system boundary should strictly encompass the energy resource in the ground (known as the 'cradle' - for example, oil in the well or coal at the mine). In contrast, the downstream boundary is known as the 'gate' [hence, 'cradle-to-gate' (Hammond and Jones, 2011a)]. Thus, in the case of an electricity system (such as that for the UK analysed by Hammond, Howard and Jones, 2013), the downstream boundary was the national electricity transmission network downstream of the various power generators. Consequently, it effectively accounts for all UK power sector primary energy use (and associated emissions). Energy analysis (EA) yields the whole-life or 'Gross Energy Requirement' (GER) of the product or service system, sometimes loosely termed the primary 'energy cost' (Allen *et al.*, 2008; Hammond and Jones, 2008; Roberts, 1978; Slessor, 1978). Likewise, the sum of all primary energies required to yield one unit of delivered energy is known as the 'Energy Requirement of Energy' (Slessor, 1978 and 1988). Thus, the sum of all the outputs from this system multiplied by their individual energy requirements must be equal to the sum of inputs multiplied by their individual requirements. The process consequently implies the identification of feedback loops, such as the indirect or 'embodied', energy requirements for materials and capital

inputs (Hammond and Jones, 2008). This procedure is indicated schematically in Figure 3,, which has been adapted from one given by Slessor (1978). Energy analysis has been widely used since the first oil crisis of the early 1970s (Hammond and Winnett, 2006).

Different 'levels of regression' may be employed (see Figure 3) depending on the extent to which feedback loops are accounted for, or the degree of accuracy wanted (Slessor, 1978; Hammond and Winnett, 2006). A first level of analysis includes only the direct energy consumption. It is normally expected that the results of a first level analysis will represent the majority of the life-cycle energy. This does not, however, imply that a first level analysis is sufficient on its own, as this is rarely the case. A second level of analysis (see again Figure 3) additionally considers energy that is required to manufacture feedstock materials (material production energy). It has been estimated that in many cases a second order of analysis can account for 90% of the total life-cycle energy (Slessor, 1978). Whilst this may hold true for many building materials, there will be many systems and activities that fall outside of this 'rule of thumb'. Analysis beyond this level is time consuming and hence studies of this order and above are rare. A third level of analysis includes energy consumed whilst manufacturing capital equipment (energy required to manufacture machines). And finally the machines from the third level of analysis are themselves manufactured from other machines (Figure 3). As such, a fourth level of analysis exists, in principle. Undertaking a study at Level 4 regression would be the most accurate, but it would necessarily be costly in both time and financial terms. In a case where similar materials or devices were to be studied, then it is desirable to carry out the initial study with greatest rigour (Level 4 regression). Subsequently, a more practical choice of regression level could be made depending on the accuracy required; perhaps Level 2 or 3 (Figure 3). This approach can be used to determine the least energy-intensive industrial process from amongst a number of alternative options.

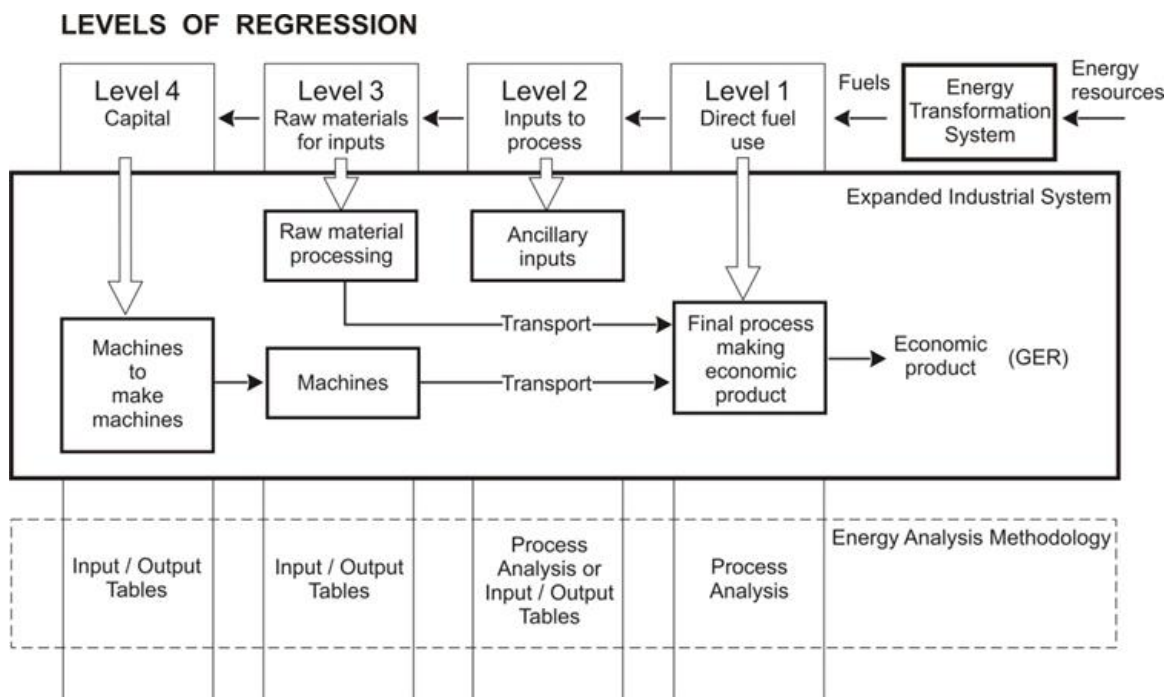


Figure 3. Schematic representation of the energy analysis process. [Source: Allen et al., 2008; adapted from Slessor, 1978].

Several differing methods of EA have been developed, and they are also indicated again in Figure 3. The most significant of these are statistical analysis, Input-Output (I-O) analysis, process analysis (or energy 'flow charting'), and hybrid analysis (Allen *et al.*, 2008; Hammond and Jones, 2008; Roberts, 1978; Slesser, 1978). The first method is limited by the available statistical data for the whole economy or a particular industry, as well as the level of its disaggregation. Statistical analysis often provides a reasonable estimate of the primary energy cost of products classified by industry. However, it cannot account for indirect energy requirements or distinguish between the different outputs from the same industry (Roberts, 1978). Input/output table analysis, originally developed by economists (Hammond and Winnett, 2006), can be utilised to determine indirect energy inputs and thereby provide a much better estimate of embodied energy. Many countries, including the UK, periodically produce inter-industry tabular datasets (one great table or matrix) depicting what each industrial category sells to and buys from other industries. Such tables can be converted from monetary values to yield data on an energy basis (Hammond and Jones, 2008). The sum of direct energies for a particular industry then adds up to the embodied energy in specific outputs (products) of that industry (Chapman, 1976; Roberts, 1978; Slesser, 1978; Boustead and Hancock, 1979) presented in terms of what are commonly known as 'energy intensities' (kJ/£ of product in the case of the UK (Hammond and Jones, 2008)). Energy input/output table analysis is limited by the level of disaggregation (i.e., the number of rows and columns) in national input/output tables and by issues associated with allocation between multiple outputs from a particular industry (sometimes referred to as co-products). Process energy analysis is the most detailed of the methods and is usually applied to a particular process or industry. It requires process flow charting using conventions originally adopted by the *International Federation of Institutes of Advanced Studies* in 1974–1975 (Chapman, 1976; Roberts, 1978; Slesser, 1978 and 1988; Boustead and Hancock, 1979). The application domains of these various methods overlap.

3.2 ENVIRONMENTAL LIFE-CYCLE ASSESSMENT (LCA)

Energy analysis preceded LCA and as such they share much of the same fundamental methodology. In order to evaluate the environmental consequences of a product or activity the impact resulting from each stage of its life-cycle must be considered. This led to the development of ecotoxicology, or a study of the harmful effects of releasing chemicals into the environment, and a range of analytical techniques that now come under the 'umbrella' of life-cycle assessment. The aim of the LCA is often to identify opportunities for environmental improvement (Allen *et al.*, 2008) by detecting the areas with the most significant impacts. In a full or detailed LCA, the energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole life-cycle, 'from cradle-to-grave' (Guinée *et al.*, 2002; Baumann and Tillman, 2004; Udo de Haes and Heijungs, 2007; Vogtländer, 2010; Curran, 2012). In the production and supply of fuels and electricity, the downstream boundary is effectively taken as the point of fuel or electricity end-use: in the home, by the commercial service provider, or in the factory. An LCA is often geographically diverse; that is, the energy and material inputs to a product may be drawn from any continent or geo-political region of the world.

The methodology of LCA was originally codified under the auspices of *the Society of Environmental Toxicology and Chemistry* (SETAC) at a series of workshops in the early 1990s (Graedel and Allenby, 1995; Udo de Haes and Heijungs, 2007). This framework subsequently

formed the basis of the *International Organization for Standardization* (ISO) 14040 series of standards: ISO 14040–14044 (produced over the period 1997– 2006). There are four main stages of an LCA (ISO 2006a and 2006b) which are shown in Figure 4 to follow a logical sequence of goal definition and scoping (outlining aims, methodology and boundary conditions), inventory analysis (data collection - determining inputs and outputs of materials, fuels, and process emissions), impact assessment (determination of the life-cycle environmental impacts for the pre-determined inventory), and Interpretation (identification of hotspots, recommendations for improvement, and treatment of uncertainty). There are many technical issues that need to be addressed during the conduct of life-cycle assessment (Graedel and Allenby, 1995; Hammond and Winnett, 2006; Udo de Haes and Heijungs, 2007; Hammond and Jones, 2008). These include the definition of system boundaries, the quality of data available, and the way the results are normalised (Hammond and Winnett, 2006; Udo de Haes and Heijungs, 2007; Hammond and Jones, 2008).

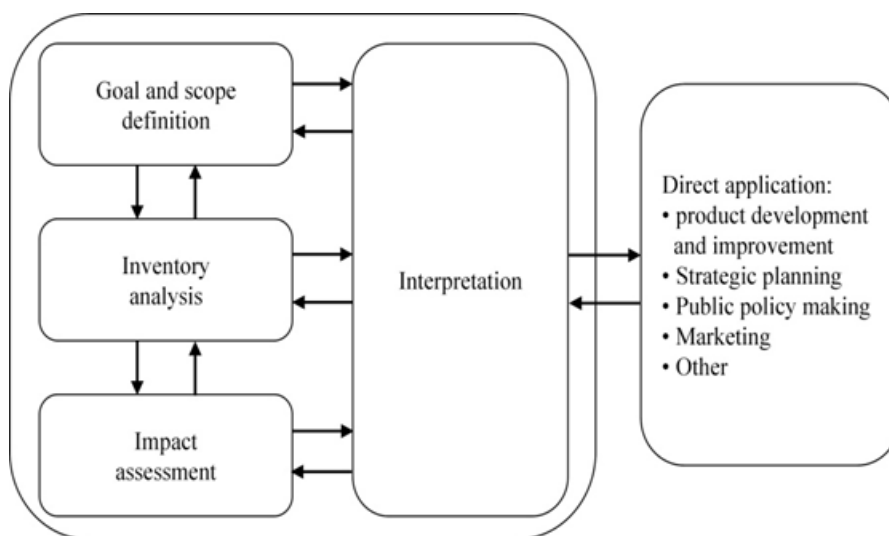


Figure 4. The four main stages of environmental LCA [Source: Allen *et al.*, 2008; adapted from ISO, 2006a and 2006b].

4. THE STAGES OF LIFE-CYCLE ASSESSMENT AND THEIR LIMITATIONS

4.1 GOAL AND SCOPE DEFINITION

The goal definition process (see Figure 4) is important as part of the planning stage for an LCA study. Here the issues to be examined are identified and the boundaries of the study clearly defined (Guinée *et al.*, 2002; ISO 2006a and 2006b; Curran, 2012). The objectives or goals of an LCA study are usually to assess impacts associated with various known environmental problems, such as global warming, acid rain and pollution of ground water. Consequently, the first task would be to specify the main processes in the life-cycle of the energy system under consideration (Reap *et al.*, 2008a). This is often assisted by the use of ‘flow charting’ (Baumann and Tillman, 2004) or systems models. Figure 5 displays an example of flow chart or model for a combined heat and power (CHP), or ‘co-generation’, plant (Hammond, 2004). Ideally, all inputs and outputs of a system should be tracked, both upstream and downstream, to the point of elementary flows of energy and materials. However, decisions on the inclusion or exclusion of specific processes [the so-called ‘cut-off criteria’ (Baumann and Tillman, 2004)] are often made on practical, rather than scientific, considerations (Suh *et al.*, 2004). This issue is similar to the one related to the ‘level of

regression' employed in energy analysis discussed above (Slessor, 1978; Hammond and Winnett, 2006). The adoption of severe cut-off criteria gives rise to the penalty of increased data costs, whereas one that is insufficient will lead to the exclusion of consequential flows (Reap *et al.*, 2008a).

The choices and assumptions made when establishing the system boundaries, and which processes to include within these boundaries, are often critical to the outcome of an LCA study (Rebitzer *et al.*, 2004). Three types of system boundaries typically exist: the boundary between the technical system and the environment, that between the technical system and other technical systems, and that between consequential and inconsequential processes. It is necessary to pinpoint the processes that are considered to contribute significantly to the overall burden of a system or its function. Setting these formal boundary conditions can prove difficult as little may be known of the impact of a system in advance, particularly for an emerging technology. Initially, the system being studied can be compared with the extensive literature of published LCA studies of similar systems, which will help identify the processes that are deemed significant. Efforts must then be focused on these processes, systematically following flows, both upstream and downstream, to reach as close to elementary flows as is reasonably attainable. Subsequently, the importance of such processes can then be investigated by carrying out in a full LCA, which can then be refined and improved in iterative loops until the required level of accuracy has been achieved (Finnveden *et al.*, 2009). Consistency must be maintained across system boundaries during a comparative assessment in order to allow systems to be compared on a like for like basis. System boundaries for LCA studies are often geographically diverse (Baumann and Tillman, 2004; Udo de Haes and Heijungs, 2007); that is, the energy and material inputs to a product may be drawn from any continent or geo-political region of the world. Udo de Haes and Heijungs (2007) suggest that LCA studies typically stop before the capital goods (i.e., the equivalent of Level 3 regression in EA), although they acknowledge that this choice is arbitrary.

As part of the scoping exercise, a functional unit needs to be defined in order to normalise data. This unit represents a quantitative measure of the service performance attributed to the system being assessed, typically per unit output (e.g., kWh of electricity or heat in the case of an energy system). This process can be complicated due to the generation of multiple outputs from the system under study (Rebitzer *et al.*, 2004; Reap *et al.*, 2008a). Thus, a CHP plant (see Figure 5) will give rise to both heat and power outputs that vary with its Power-to-Heat Ratio (Hammond, 2004). These 'allocation' problems therefore stem from the need to associate flows from such multi-functional systems (Baumann and Tillman, 2004; Reap *et al.*, 2008a). They are regarded as one of the most controversial issues within the scope of LCA (Rebitzer *et al.*, 2004; Reap *et al.*, 2008a). Multiple outputs are often partitioned in relation to some physical property associated with the output, such as its mass, energy content, exergy (Hammond, 2004), or economic value (Rebitzer *et al.*, 2004; Reap *et al.*, 2008a). The adequacy and feasibility of various allocation methods has been critically reviewed by Ekvall and Finnveden (2001). They assert that ISO methods (ISO, 2006b) whereby (i) system boundaries for the studied processes or technologies are expanded to include alternative options (Ness *et al.*, 2007); a subdivision of the system into sub-processes; or (iii) an allocation scheme based on physical causal relationship (as suggested earlier); all potentially yield accurate information on the environmental burdens. However, each procedure brings with it limitation and difficulties (Ekvall and Finnveden, 2001; Rebitzer *et al.*,

2004; Reap *et al.*, 2008a). It is the view of Ekvall and Finnveden (2001) that further research on LCA allocation issues is required, and that ISO should revise the allocation procedures currently encompassed within its guidelines (ISO 2006a and 2006b).

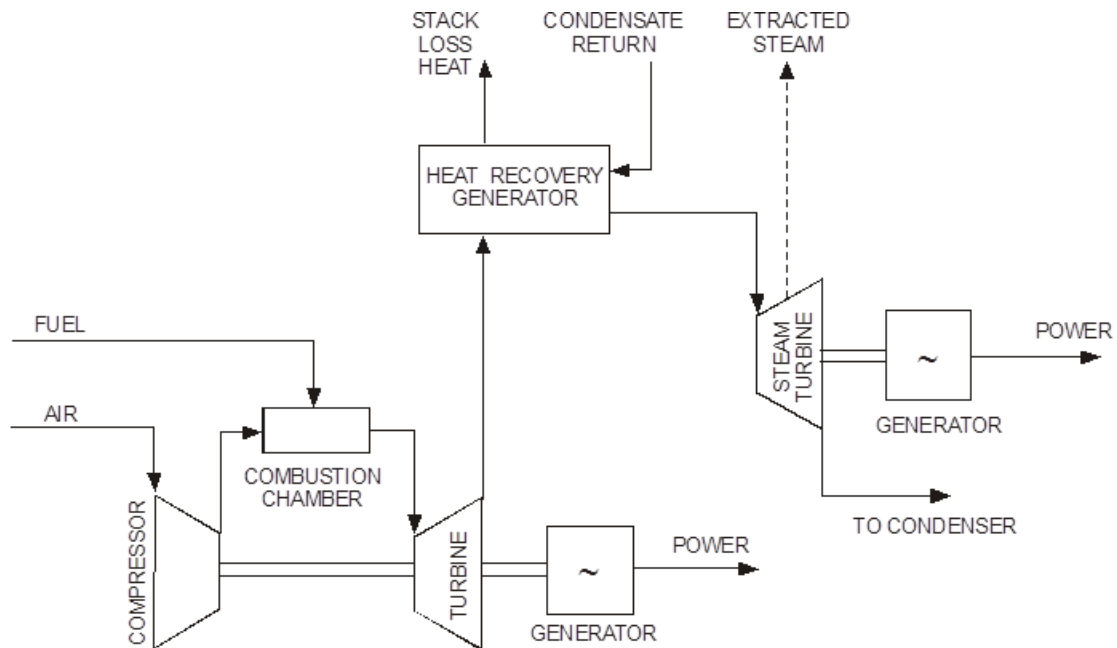


Figure 5. An industrial combined cycle gas turbine plant (with and without extracted steam for process heating; dashed line). [Source: Hammond, 2004; adapted from Bilgen, 2000].

4.2 INVENTORY ANALYSIS

To undertake a full or detailed LCA study requires a vast amount of data, much of which is not within the public domain (Guinée *et al.*, 2002; Baumann and Tillman, 2004; ISO 2006a and 2006b; Curran, 2012). The data-gathering phase can be time-consuming (Hammond and Winnett, 2006), and makes use of two main information sources: archival journal articles, as well as 'grey' literature from the Internet (Curran, 2012). Credible databases for the Life Cycle Inventory (LCI) stage (see Figure 4) are now available with the rise in popularity of LCA, and these can be purchased either as a commercial database or as part of a software package. There has been a call by the Society for Promotion of Life-Cycle Development (SPOLD) for all LCA databases to be in the same format (Rebitzer *et al.*, 2004; Hammond and Winnett, 2006), thereby making data transfer easier. To some extent this is taking place, but the use of LCA is still rather too limited to enable a practitioner to find all the information needed from a public database. LCI models are typically static (i.e., time is not used as a variable) and all relationships are presumed to be simple linear ones both in regard to system processes and the processes in the environment (Baumann and Tillman, 2004; Udo de Haes and Heijungs, 2007). One specific data quality problem is known as 'local technical uniqueness' (Reap *et al.*, 2008a). This arises because extraction, production, distribution, and end-of-life technologies vary with their location. Consequently, the types and amounts of resources demanded, and wastes produced from their transformation, are unique. Reap *et al.* (2008a) observed, for example, that the environmental burdens associated with electricity production vary with the generation mix and their siting. It is therefore inappropriate to

employ average or generic data or models. Ayres (1995) also noted that such generic process descriptions often differ from those found in practice.

4.3 IMPACT ASSESSMENT

The Life Cycle Impact Assessment (LCIA) phase (see Figure 4) consists of three mandatory sub-stages: selection of impact categories, 'Classification', and 'Characterisation' (ISO 2006a and 2006b). Firstly, the impact categories and impact methods need to be selected. However, selecting environmental impact categories effectively introduces truncation and associated inaccuracies (Reap *et al.*, 2008b). The *Classification* sub-stage is where the data is split into and assigned to the relevant categories, e.g., GHG emissions, emissions to water, etc., which usually occurs naturally as part of the data gathering process. The data then undergoes *Characterisation* (SETAC, 1991), a process that seeks to quantify the relative contributions to each environmental problem, e.g., global warming potential. There are also three additional optional elements to LCIA, namely; normalisation, grouping and weighting (ISO, 2006a and 2006b). Impact categories can be compared to a reference, grouped/ranked and/or given relative weights in order to facilitate comparisons between them. These processes are subjective (Reap *et al.*, 2008b), and many different methods are currently in use (Hammond and Winnett, 2006). This leads to inevitable problems when the results of LCIA are interpreted.

4.4 INTERPRETATION AND IMPROVEMENT EVALUATION

Interpretation is a critical stage in LCA, particularly for energy systems, as it often used as a quantitative basis to form policy and aid decision making. The main premise of this stage (see Figure 4) is to identify potential environmental improvements (Guinée *et al.*, 2002; Baumann and Tillman, 2004; ISO 2006a and 2006b; Curran, 2012). It enables improvement strategies to be developed for any of the life-cycle processes. Those that exhibit large environmental impacts can be further analysed to see if there are alternative options for reducing the impact of the product, system, or activity. Once the life-cycle processes with the larger single impacts have been determined, then it is important to examine whether there are any other stages which (taken together) could have a significant effect on the overall performance (Hammond and Winnett, 2006). LCA is invaluable for identifying such contributions, and this helps to make it an important, some would argue comprehensive, environmental management tool. Characterisation factors vary linearly between inventory data and impact or stressor category indicators (Pennington *et al.*, 2004) and aid comparison across categories. Pennington *et al.* (2004) argue that further research is needed in order to support integrated decision-making by way of comparisons being made across stressor categories (global warming, toxicological effects, etc.) and areas for protection (resource consumption, human health, impacts on ecosystems, etc.). However, Reap *et al.* (2008b) argue that the overarching problem with interpretation is in terms of aggregation: collapsing inventory or impact data into a single 'figure of merit'. They also observe that variability in the modelled systems and inaccuracies in other LCA stages results in a high degree of aggregate uncertainty.

5. THE STRENGTHS AND WEAKNESSES OF LCA: A SWOT-LIKE ANALYSIS

5.1 BACKGROUND

SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis is traditionally a management tool used in structured planning to strategically evaluate a project or business venture. However, in this instance, it will be utilised somewhat unconventionally, to provide a framework for identifying the strength and weaknesses of LCA methods in relation to energy systems. Assessment of the environmental performance of energy systems has attracted substantial energy, environmental and climate change policy interest. Many journals have been published in this policy arena. This analysis highlights the suitability of various LCA methods as part of the process of technology assessment of energy systems, and pinpoints the best use for each energy options from an environmental perspective. The key strengths and weaknesses identified and discussed below have been summarised in Table 1.

Table 1. An outline of strengths and weaknesses of environmental LCA

Strengths	Weaknesses
Holistic environmental appraisal	Static/Snapshot assessments
Established international standards	Variation in assessment due to value choice/ methodological approaches
Procedural transparency	Only predefined environmental impacts assessed
Allows level playing field for comparison	A target for sustainable activity not specified only embodied impacts quantified
Pinpoints environmental/inefficient hotspots	Data quality
Springboard for communication	Inaccessible results

5.2 STRENGTHS

5.2.1 *Holistic environmental appraisal*

LCA is a powerful tool for assessing and inspecting all processes that are linked with an energy system. The full system is analysed over its entire lifecycle, from 'cradle-to-grave' (Baumann and Tillman, 2004; Vogtländer, 2010; Hammond and Jones, 2011a), scrutinising each process from the acquisition of raw material, production, use and disposal. LCA is a comprehensive tool that can be used to assess a wide set of pre-determined environmental categories, and providing a full account of the environmental performance of an energy system. Furthermore, LCA ensures that problem shifting is avoided by encompassing every life-cycle stage of the energy system, while covering this wide range of environmental issues. Otherwise, life-cycle stages could be omitted from the analysis (Bhat and Prakash, 2009) and, consequently, decision makers might be erroneously provided with incomplete data. This is particular significant in the assessment of energy systems which have wide-ranging upstream emissions which are habitually omitted in

assessments that form the basis of important policy strategy (Hammond, Howard and Jones, 2013; Hammond and O’Grady, 2014). Additionally the macro-scale insights gained from a life-cycle approach, of both upstream and downstream effects, has the potential to add value to many technology assessments be that economic, social or environmental (Thabrew, Wiek and Ries, R. 2009). Life-cycle thinking is becoming fundamental to how to ‘conceptualize environmental issues’ and also the way to address them (Heiskanen, 2002).

5.2.2 *Established Standards*

The ISO 14040 series dealing with their LCA guidelines and standards (ISO 2006a and 2006b) were refined and modified based on the years of experience, thereby yielding a broad framework. Numerous books and guidelines (Guinée *et al.*, 2002; Baumann and Tillman, 2004; Vogtländer, 2010; Curran, 2012) have been written around the topic, along with many journal papers covering a wide range of application domains. Such activities have added to LCA robustness and its knowledge basis. Despite the level of maturity achieved thus far, LCA is still encountering methodological development, with many areas of ongoing research (Finnveden *et al.*, 2009).

5.2.3 *Procedural Transparency*

Transparency is one of the foundations of any quality assessment scheme for energy systems. It must encompass the assumptions made, methodologies used, and data sources. Without this level of transparency, LCA results can prove difficult to interpret, and their reliability is greatly reduced (Herva *et al.*, 2011). Indeed, procedural transparency is one of the main underlying principles to the LCA international standards (ISO 2006a), particularly in regard to the reporting of results. The transparency of LCA results has been further enhanced by the employment of predefined impact assessment (i.e., LCIA) methods that have been tested over years, reviewed and subsequently improved (Itsubo and Inaba, 2003; Jolliet *et al.*, 2003; Pennington *et al.*, 2004; Goedkoop *et al.*, 2009). These methodologies are well understood by the LCA community and allow results to be easily reproduced once the same assumptions and system boundaries are followed. Despite a high level of procedural transparency the reporting of LCA results is often married with a lower level of transparency. This can make it difficult to integrate other studies in the literature into a new LCA model (see the ‘Weaknesses’ section further below).

5.2.4 *‘Level playing field’*

The life-cycle approaches are being realised as an essential component for schemes that compare and contrast the environmental consequences, including climate change (IPCC, 2011), of alternative energy and other systems. Hence, LCA methodologies have been variously applied as decision support tools for distinguishing between products, or services in terms of their environmental burdens on the basis of a ‘level playing field’ (Höjer *et al.*, 2008). Decision makers can then assess the environmental trade-offs associated with the adoption of specific processes or technologies (Jeswani *et al.*, 2010). Furthermore, in order to adhere to the ISO LCA standards, a third party review must be carried out so that a comparative assertion can be disclosed to the public (ISO 2006a and 2006b). This helps identify conflicting results in the interests of different stakeholders.

5.2.5 *Pinpointing environmental/inefficient ‘hotspots’*

When an energy system LCA is undertaken, a model is built that represents its entire life-cycle; therefore accounting for all processes associated with the system along with their inputs and outputs. Many LCA studies of this type are carried out in order to identify the opportunities for

process or system improvement (Allen *et al.*, 2008a) via the detection of environmental 'hotspots'. These are situations, that if not addressed, could prove deleterious to the environment and species that depend on it (including humans). Such studies provide energy system designers and policy makers with a detailed insight into the environmental implications of the energy system, allowing them to develop a strategy for system optimisation (Battisti and Corrado, 2005). Alternative process options can be explored, achieving optimum improvements, while ensuring a limit to other potential environmental consequences at full scale. A life-cycle approach can also provide for a better understanding of the resource efficiency of processes and the monetary cost associated with the manufacture and design of a process, technology or system (Azapagic, 1999). New design insights can thereby be provided, highlighting areas of inefficiency and potential avoidable costs for an energy system developer.

5.2.6 *'Spring board' for communication*

Technology developers, investors, and policy analysts, as well as environmentalists, are all pressing for the more enhanced evaluation of the environmental impacts of processes, technologies and systems. This has, in part, led to the rise in popularity of LCA. It can act as a robust quantitative basis to inform policy and contribute to a wide range of communication and marketing initiatives. Many companies, such as EDF (EDF Energy, 2013) and Siemens (2012), publish the findings of their LCA studies in the form of 'Environment Product Declarations' (EPD) to promote the merits of their products (ISO, 2006c). EPDs are verified documents – 'green yardsticks' – that report quantified environmental data for products based on LCA, and other relevant information, in accordance with ISO 14025. The data is presented in pre-set categories that include raw material acquisition, energy use, emissions to air, soil and water, and waste generation. LCA can also aid internal company or organisational communications and sustainability strategies, including the setting of goals, formulating pathways to reach these targets, and introducing sustainable procurement (Udo de Haes and Heijungs, 2007).

5.3 WEAKNESSES

5.3.1 *Static or 'snapshot' assessments*

LCA methods rely on data and assumptions based on currently prevailing technology. Due to the large uncertainty band associated with technology learning rates and LCI data/carbon emission factors, it becomes difficult to forecast likely environmental consequences into the future. If uncertainties are too high, then decision-makers may be unwilling to rely on the final results of an LCA study for guidance (Herrmann *et al.*, 2014). Lowering such uncertainties is crucial when comparing the environmental performance of an emerging technology entering the market with its counterparts. In order to reduce data requirements, 'attributorial' LCA (ALCA) attributes environmental burdens associated with the production and use of a specific process, product or service at a given instance in time. Therefore, in order to reduce data requirements, ALCA employs site-independent peer reviewed data. The analysis will consequently only reflects a typical energy system that is being assessed, and does not take into account for any site specific (Finnveden *et al.*, 2003; IPCC, 2011) or temporal factors (Levasseur *et al.*, 2010). However, these may have a large influence on its actual environmental impacts. For example, as the electricity grids undergo decarbonisation over time, technologies such as electric vehicles and heat pumps will become increasingly more dominant in terms of their contributions to the reduction of carbon emissions. Thus, traditional LCA does not measure how the results evolve as future energy system

develops. But dynamic ‘consequential’ LCA (CLCA) can be now applied in an effort to overcome this issue (Peht, 2006). CLCA seeks to identify the environmental consequences of a decision or a proposed change to a studied system (i.e., process, product or service) over time.

5.3.2 *Variation in assessment due to value choice/methodological approaches*

It is quite possible for two independent studies carried out on a given energy system, using the same method, to yield different results. This is likely to be caused by the adoption of different LCA methodological approaches and assumptions. Although LCA has a well-established framework, value judgements are required at various stages, including in regard to system boundaries, allocation methods, and end-of-life treatment (Rebitzer *et al.*, 2004; Guinée and Heijungs, 2005). Procedural transparency (see the discussion earlier) and alignment of these subjective choices is vital in order to ensure a fair comparison (ISO, 2006b). A robust interpretation phase of LCA is thus required, complete with uncertainty and sensitivity analysis, in order to enhance reliability and credibility (Pennington *et al.*, 2004).

5.3.3 *Predefined environmental impacts*

Predefined environmental impact sets offer the advantage of a robust peer reviewed method to evaluate energy system and allow for swift inter-system comparison on a comparable basis. The LCIA methods available largely converge on most environmental issues, although minor differences have been shown to lead to different results, particularly in terms of the cause of human toxicity (Dreyer, Niemann and Hauschild, 2003). Notwithstanding the fact that LCA is one of the most comprehensive environmental appraisal tools, not all relevant environmental issues are covered (Finnveden, 2000). Furthermore, current LCIA methods have an inherent bias in addressing certain environmental impacts where data is more readily available. For example, LCA has a particular focus on impacts of emissions to air and to resource depletion, which are two dominant impacts of traditional (fossil fuel-based) energy systems. In contrast, impacts connected with land use (Schmidt, 2008) and radiation (Finnveden *et al.*, 2003) are much less robustly addressed. Consequently, LCA is less well-equipped to assess particular low carbon energy systems, such as those associated with bioenergy and nuclear power.

5.3.4 *Relevance to wider global environmental issues*

LCA can quantify, as indicated above, the potential environmental performance of an energy system in predefined environmental impact categories. However, it does not relate this impact to a particular frame of reference or benchmark (Nissinen *et al.*, 2007). This makes it difficult to establish what the results mean on a regional or global scale. Often results undergo normalisation in order to add this dimension, i.e., comparing the results to the average emissions per capita on a regional or global scale. Nevertheless, this still does not give results in the context of a minimum sustainability target for a given activity, or its impact on a wider scale.

5.3.5 *Data quality*

Like any type of modelling, LCA methodologies are susceptible to the possibility of poor quality of input data (see Section 4.2). Clearly the more robust the input data, the better and more reliable the final results will be. Obtaining data of good quality that reflects accurately the energy system being assessed can prove to be challenging. This is particularly true with novel or emergent technologies, where processes and materials used are being developed throughout the research, development and demonstration (RD&D) process (Hetherington *et al.*, 2013). In certain circumstances, data quality and quantity is insufficient to support a comprehensive LCA.

Companies and organisations may be unwilling to share data due to confidentiality agreements or lack of a whole life-cycle perspective (Hammond and Seth, 2013). This can greatly add to the uncertainty of these assessments methods, reducing their overall credibility and influence.

5.3.6 Inaccessible results

In order to deliver an accurate account of the environmental performance of an energy system, numerous possible environmental consequences need to be addressed and evaluated. LCA provides one of the most comprehensive assessment methods for this purpose, although the results may be incomprehensible to non-specialists (Nissinen *et al.*, 2007). Final LCA reports can often prove rather technical, steeped in heavy terminology, and comprising of lists of unfamiliar environmental mechanisms and impacts (see Figure 6). To ensure greater community-wide value is extracted from life-cycle assessments, the information must be transformed into a more accessible and useable form. Sensitivity analysis and improvement analysis may then be required after the LCIA stage in order to interpret the results. This would help formulate useful LCA-related recommendations that can be fed into a given decision-making process.

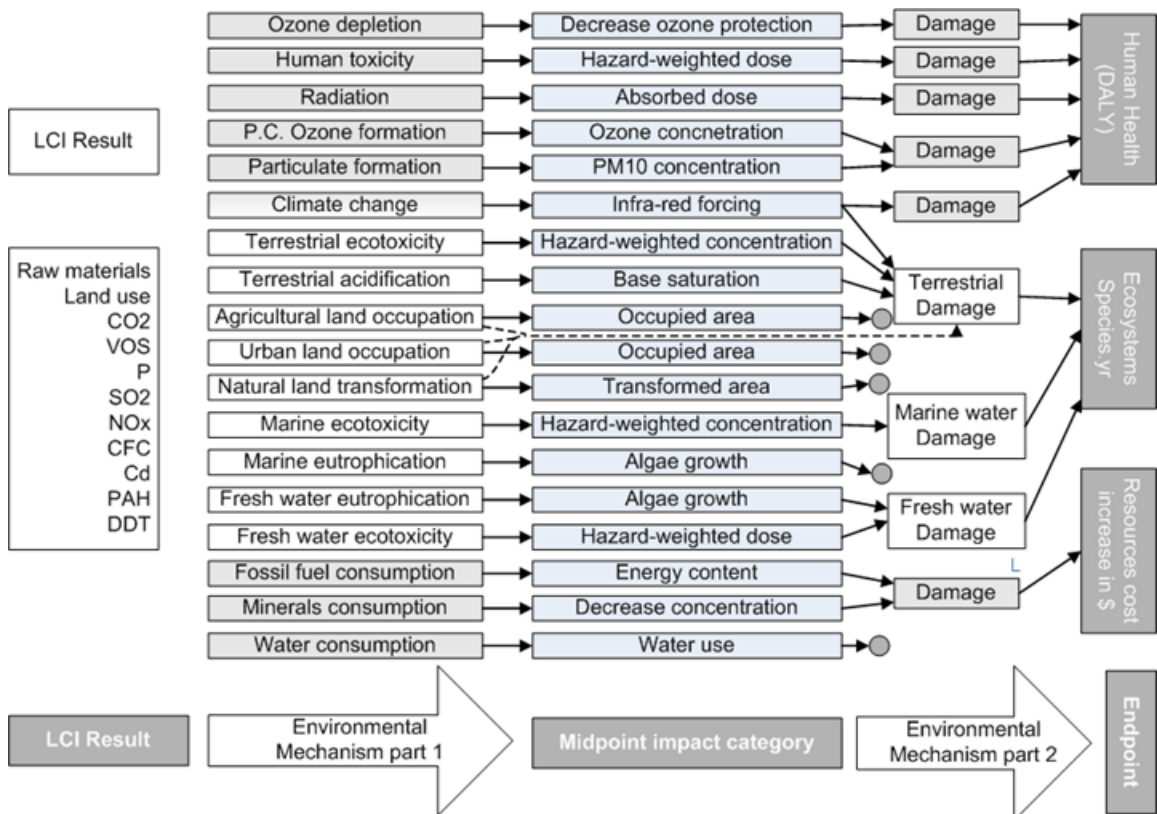


Figure 6. Relationship between LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe 2008. Source: Reproduced from (Goedkoop M.J. et al., 2009).

6. ILLUSTRATIVE LCA ENERGY SECTOR CASE STUDIES

6.1 SYSTEM BOUNDARIES

All LCA studies discussed in this section followed a cradle-to-gate system boundary, which allows users to quantify and compare the upstream environmental burdens associated with different options and energy carriers that are consumed. The main life cycle stages and processes included

within the system boundaries of these studies are illustrated in figure 7. These studies were carried out using a bottom-up process approach, which allows the contributing factors to the overall cumulative results to be more transparently assessed. Equally, such an approach allows the system boundaries to be clearly defined and facilitates the assessment of the impact of alterations to the system through sensitivity analysis. In contrast, the low level resolution in studies using input–output LCA approach (Finnveden et al., 2009) excludes their use from the primary application of many LCA studies, such as system redesign or material selection.

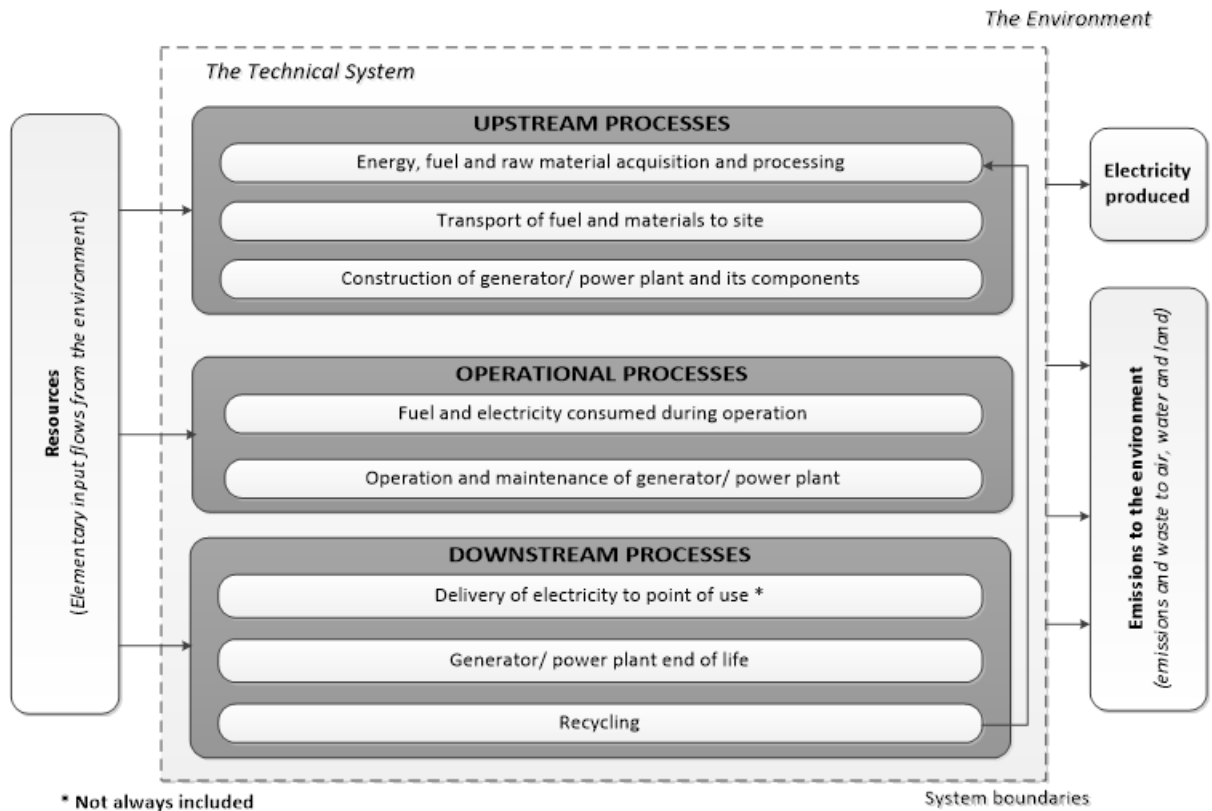


Figure 7. System boundaries for 'cradle to gate' life cycle assessment of electricity production.

6.2 TRANSITION PATHWAYS TO A MORE ELECTRIC, LOW CARBON UK ECONOMY

6.2.1 Background

A multidisciplinary team of UK engineers, social scientists, policy analysts and innovation specialists have recently sought to develop and explore three 'transition pathways' towards a UK low carbon electricity system in 2050 (Foxon *et al.*, 2010; Hammond and Pearson, 2013). The starting point in the development of these UK transition pathways, unlike many scenario-building exercises, was the governance framings or 'logics' of key actors will be a crucial influence on any pathway towards a future low-carbon, UK energy system. This study has focused on the choices and actions needed to 'get there from here', and on the analysis of the pathways' technical, socio-economic and environmental implications. An innovative, robust, and 'whole systems' evidence base has therefore been developed that is distinctive from those devised elsewhere in the UK energy research community (Hammond and Pearson, 2013). Stakeholder workshops were employed by the consortium to distinguish the logics of three core sets of actors: those of the market, government and civil society. Consequently, the three transition pathways were named *Market Rules (MR)*, *Central Co-ordination (CC)* and *Thousand Flowers (TF)* respectively; each being

dominated by a single group's logic (Foxon *et al.*, 2010; Hammond and Pearson, 2013). This approach builds *inter alia* on approaches originally devised by Dutch researchers (e.g., Rip and Kemp, 1998; Geels, 2002). Thus the consortium applied a multi-level perspective for analysing socio-technical transitions, based on interactions at and between three levels: *niche innovations*, *socio-technical regimes*, and *macro-landscape pressures* [see Figure 8 (Foxon *et al.*, 2010)]. The pathways are not predictions or roadmaps; rather they are a way of imaginatively exploring future possibilities, to inform proactive and protective decision making and enhance the potential for building consensus towards common goals.

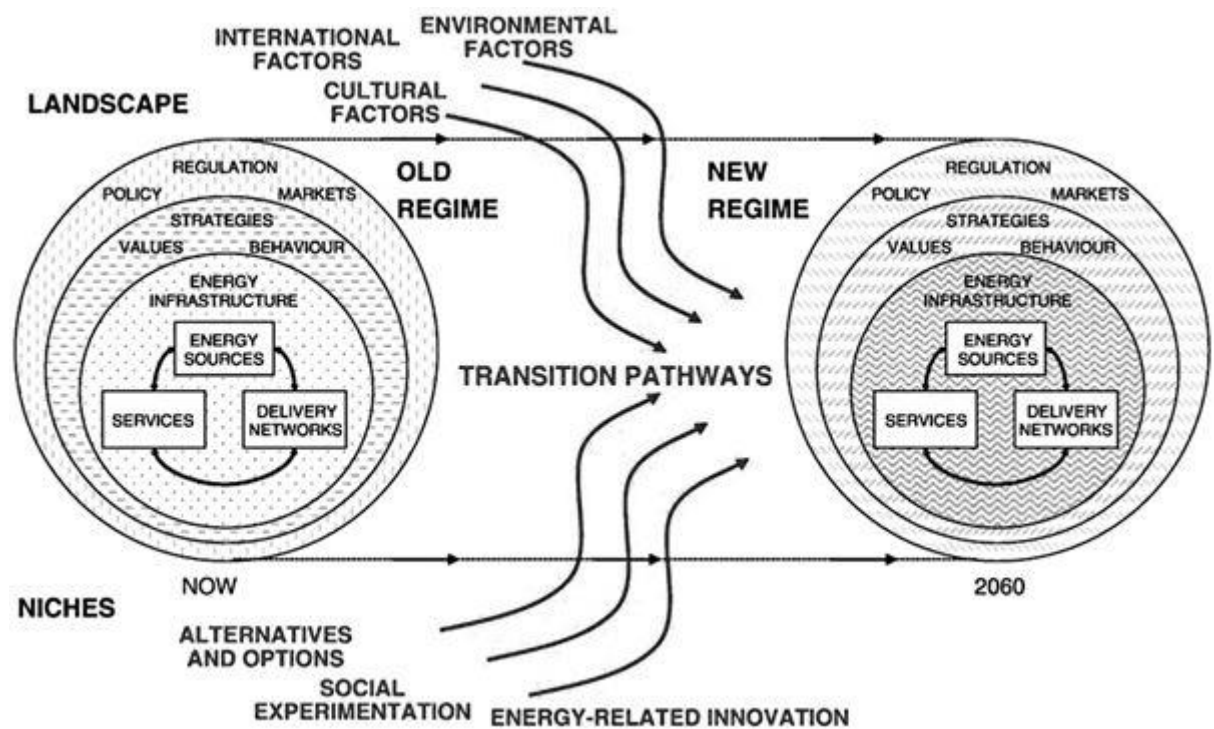


Figure 8. Possible transition pathways and the factors that influence them. [Source: Hammond and O'Grady, 2014; adapted from the Transition Pathways Consortium (Foxon *et al.*, 2010)]

The whole systems appraisal of *Version 1.1* of the above transition pathways was undertaken (Hammond, Howard and Jones, 2013) within an overarching sustainability framework (Hammond and Jones, 2011). They were subsequently updated and improved by Hammond and O'Grady (2014) in terms of the revised *Version 2.1* of the pathways. These studies built on earlier studies of simpler power networks (El-Fadel *et al.*, 2011) and individual energy technologies (Hammond *et al.*, 2011a). The impact of the three pathways has been assessed using energy analysis and environmental life cycle assessment (LCA) on a 'whole systems' basis: from 'cradle-to-gate' (Hammond, Howard and Jones, 2013). 'Whole system' GHG emissions are the sum of upstream and operational emissions. The latter ('stack') emissions are those directly associated with the combustion of fossil fuels within power stations. Thus, the whole system emissions amount to those related to the '*Energy Transformation System*' as defined by way of Figure 9. Hammond, Howard and Jones (2013) and Hammond and O'Grady (2014) both highlighted the significance of 'upstream emissions' and their (technological and policy) implications, in contrast to the emphasis on power plant operational emissions conventionally presented by other analysts. Upstream environmental burdens arise from the need to expend energy resources in order to extract and

deliver, for example, fuel to a power station. They include the energy requirements for extraction, processing/refining, transport, and fabrication, as well as methane leakages that occur in coal mining activities (a major contribution) and from natural gas pipelines.

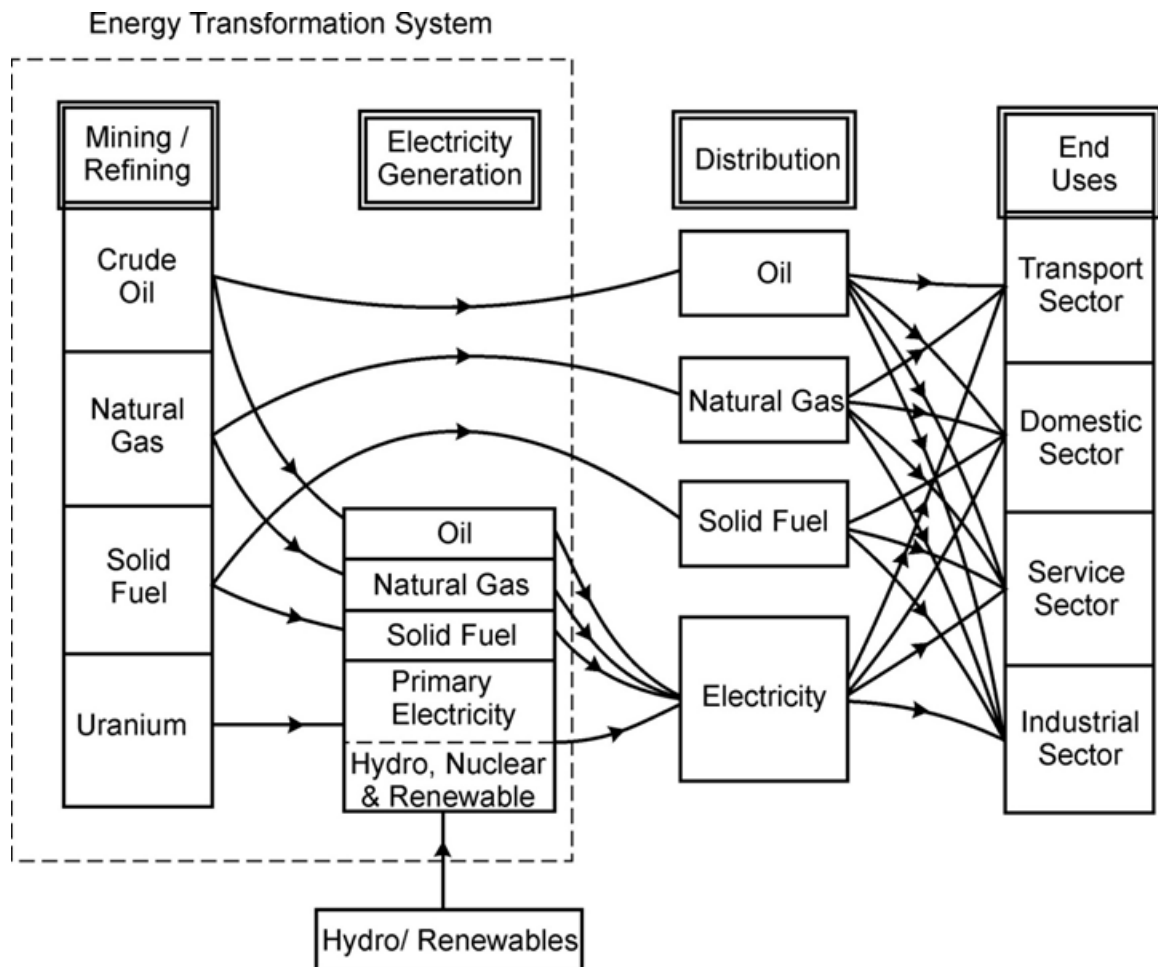


Figure 8. A simplified representation of the UK energy system. [Source: Hammond, 2000].

6.2.2 Life-cycle Energy and Environmental Performance of the UK Transition Pathways

The LCA software package *SimaPro* was used for the transition pathway studies by Hammond, Howard and Jones (2013) and Hammond and O'Grady (2014) [following Allen *et al.* (2008a)]. It is a commercial package developed from that originally developed at the Institute of Environmental Sciences (CML), Leiden University, The Netherlands (Guinée *et al.*, 2002). This software enables the manipulation and examination of inventory data in accordance with the ISO LCA Standards (ISO, 2006a and 2006b). ReCiPe 2008 was selected as the impact assessment method (Goedkoop *et al.*, 2009). This method harmonises and builds on both the midpoint approach 'CML 2002' and endpoint approach 'Eco-indicator 99', allowing both modelling approaches to be employed in the same framework (as shown in Figure 6). Characterisation at the midpoint level reveals the strength of the environmental stressor at a common midpoint along the cause-effect chain, whereas characterisation at the endpoint level endeavours to quantify the potential damage to the areas of protection (resource consumption, human health, impacts on ecosystems, etc.). In this analysis, midpoint modelling was employed as it carries less inherent uncertainties and less

aggregated results than in endpoint modelling, of which is still regarded as a new field in LCIA (Hauschild *et al.*, 2013).

6.2.3 GHG Emissions from the UK Electricity Sector

Projected ‘whole systems’ carbon emissions (i.e., operational or ‘stack’, plus upstream emissions) from the UK *Electricity Supply Industry* (ESI) [Mt CO_{2e}] under all three *Version 2.1* transition pathways over 1990-2050 are shown in Figure 10 (Hammond and O’Grady, 2014). In contrast, the power generator shares of the UK carbon intensity (kg CO_{2e}/kWh_e) in 2050 under each of the *Version 2.1* pathways are illustrated in Figure 11 (Hammond and O’Grady, 2014). The coal carbon capture and storage (CCS) share of emissions is seen to fall significantly from the MR pathway through CC to its lowest value for TF. Its dominance is largely replaced by CHP generation. Nuclear power plays the more significant role in CO₂ reductions under the CC pathway. Large-scale renewables have a major influence by 2050 under the CC pathway and, particularly, the TF pathway [see again Figure 11]. Similar trends were seen in *Version 1.1* with minor changes made to key technologies, especially in TF pathway. Coal CCS has less dominance under *Version 2.1*, while gas CCS, wind and nuclear power share increased in both MR and CC pathways. In contrast, the role of coal CCS, gas CCS and nuclear power was reduced in TF pathway, and replaced mainly by CHP.

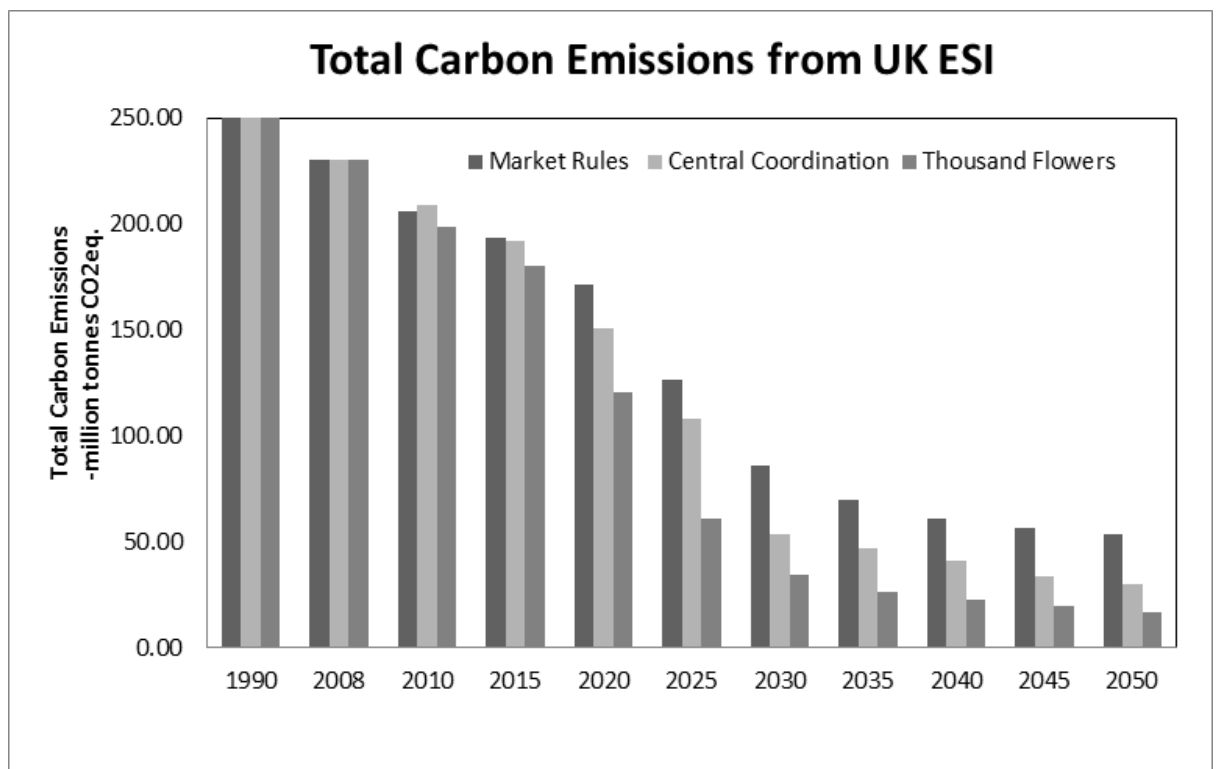


Figure 10. Projected ‘whole systems’ carbon emissions from the UK electricity sector (Mt CO_{2e}) 1990-2050 under the three Transition Pathways - Version 2.1. [Source: Hammond and O’Grady, 2014].

The *Version 2.1* transition pathways (see, for example, Figure 10) suggest that, taking account of upstream emissions, there might actually be a fall in carbon emissions from the UK power generation sector of some 31-51% by 2020, 65-86% by 2030, and 78-93% in 2050. The lower figures relate to the MR pathway, whilst the higher ones are associated with the *Thousand Flowers* pathway. The British Government’s independent *Committee on Climate Change* (CCC)

advocated deep cuts in power sector operational emissions through the 2020s (CCC, 2010), with UK electricity generation largely decarbonised by 2030-2040. In contrast, the present transition pathways (see again Figure 10) projections indicate that the UK ESI could not be fully decarbonised by 2050 on the ‘whole systems’ basis employed in the process-LCA studies of Hammond, Howard and Jones (2013) and Hammond and O’Grady (2014). This is because the present estimates take account of upstream, fugitive GHG emissions, whereas the projections by bodies like the CCC and *Department of Energy and Climate Change* (DECC) do not. Nevertheless, the transition pathways suggest that the ESI will be able to bear a significant share of the overall 80% carbon reduction target by 2050. The CCC analysis suggests that their projections would lead to average operational emissions from generation falling to around 50gCO₂/kWh_e by 2030 (CCC, 2010). In contrast, the present MR pathway (Figure 10) indicates that ‘whole system’ emissions from the UK ESI are likely to only fall, accounting for upstream emissions, to ~202 gCO_{2e}/kWh_e by 2030 and ~105 gCO_{2e}/kWh_e by 2050. Even the least impactful pathway TF, indicates emissions falling to only ~108 gCO_{2e}/kWh_e by 2030 and ~53 gCO_{2e}/kWh_e by 2050. If the UK is to genuinely meet its stringent carbon reduction targets, then it will therefore be necessary to account for upstream emissions from power generation of the type evaluated here by Hammond, Howard and Jones (2013) and Hammond and O’Grady (2014). Otherwise, even if the current UK carbon reduction targets are met, there will remain further emissions upstream.

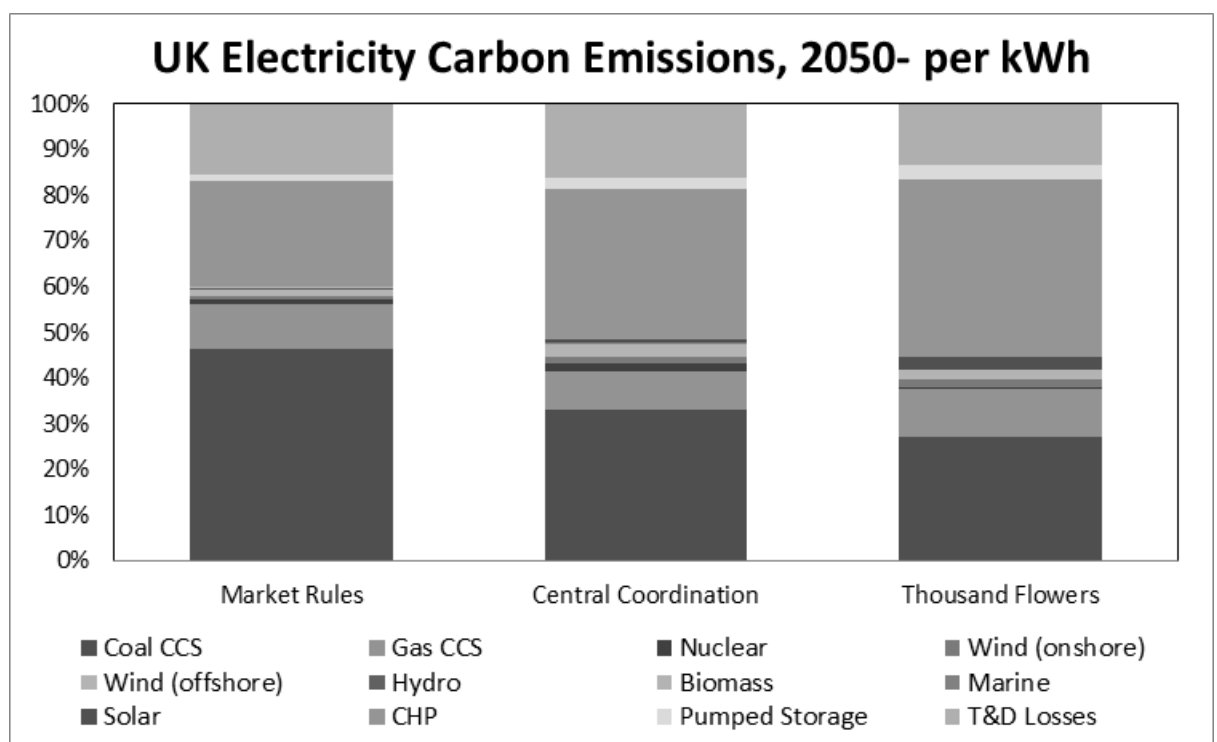


Figure 11 .UK power generator shares of the ‘whole systems’ carbon intensity (kg CO_{2e}/kWh_e) in 2050 under each of the Three Transition Pathways - Version2.1. [Source: Hammond and O’Grady, 2014].

6.2.4 Other Life-cycle Environmental Impacts from the UK Electricity Sector

The *Version 1.1* transition pathway process LCA studied by Hammond, Howard and Jones (2013) was terminated at the normalisation stage, with the results in the form of 18 different

environmental indicators. Normalisation offers a reference situation for the pressure on the environment for each LCA environmental impact category [see, for example, El-Fadel *et al.* (2010), who employed a limited set of nine impact categories]. It typically employs results in terms of so-called ‘person emission equivalents’. These normalised results, however, do not reveal which impacts are more significant (to the environment). For this to be achieved the impact categories need to be weighted, which is typically achieved by expert panel judgement. However, weighted indicators are highly subjective and have greater uncertainties (El-Fadel *et al.*, 2010). Nevertheless, it is only practical to display the results for a limited range of indicators here. The full set helped to identify and focus on key categories, and were subsequently incorporated into a single score LCA indicator (although this must be used with some caution). Three of the most significant categories or indicators in the present context were identified by Hammond, Howard and Jones (2013) to be climate change, human toxicity and particulate matter formation.

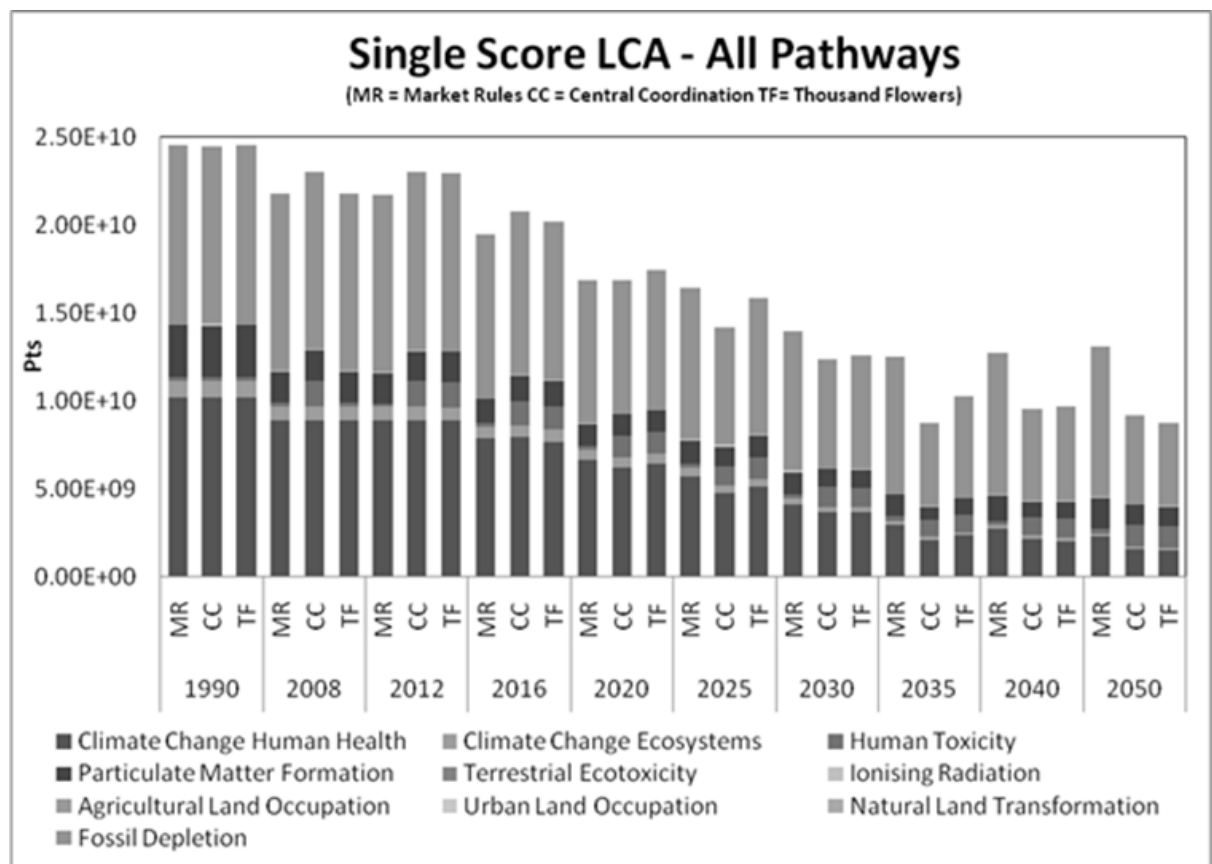


Figure 12 .‘Single Score LCA Indicator’ (Pts) attributable to the UK electricity sector 1990-2050 under each of the three Transition Pathways.[Source: Hammond, Howard and Jones, 2013]].

The LCA study by Hammond, Howard and Jones (2013) yielded estimates of pollutants or wastes released into the environment as a consequence of the power network (in terms of 18 separate impact indicators, together with a tentative ‘single score’, aggregate LCA measure). The 18 separate LCA categories can be weighed against each other. The lower the resulting score the better, although it doesn’t adequately reflect, for example, the impacts associated with nuclear power generation. Nuclear is low carbon, but has a number of other health and environmental impacts associated with the potential release of ionizing radiation from nuclear power stations and processing plants. These are generally not effectively accounted for in LCA software tools,

because they do not have a basis in ecotoxicology. Statistical weighting of the different LCA categories is normally achieved by the engagement of a panel of experts. It is therefore highly subjective, and this process would not be advisable in many cases. However, it can be a useful complimentary metric. A 'Single Score LCA' metric has been applied in the present study [see Figure 12] as an indicative measure. Default weightings from the newest, state-of-the-art, LCA interpretation methodology have been utilised (Goedkoop *et al.*, 2009). Fossil fuel depletion and GHG are given strong weightings. The units adopted are known as eco-points (or 'Pts'). They were developed as the Swiss 'Ecological Scarcity Method'. The method is based on a weighted score of each LCA impact category (i.e., climate change, human toxicity, ... etc.) that enables them to be added into a single score. The base is 100 Pts for the 1990 fuel mix. The Single Score LCA indicator for each transition pathway is indicated in Figure 12. These represent the results for the total pathway, and not per kWh_e. They can be seen to fall over the period 1990-2050, although not as steeply as for carbon emissions [contrast with the GHG emission results displayed in Figure 10]. Overall there is a 49% reduction against the 1990 baseline under the MR pathway. A 67% reduction is exhibited under the CC pathway, and almost the same reduction in the case of the TF pathway (68%).

6.3 FOSSIL-FUELLED POWER PLANTS WITH AND WITHOUT CARBON CAPTURE AND STORAGE

The operational (direct or stack) emissions associated with the combustion of fuels are compared with GHG emissions associated with upstream coal and natural gas activities in Table 2. This data indicates the magnitude of the difference between direct combustion and upstream emissions. Such fugitive GHG emissions, for example, arise from the production and transport of natural gas. They imply that the measures advocated by the CCC for decarbonising the UK economy (CCC, 2010), viewed by some as challenging, and are actually likely to be not stringent enough. The resulting impacts are highly variable depending upon source of gas: whether, for example, they come from UK natural gas fields or are imported into Britain from the Russian Federation. The gas CCS dataset interrogated here is the same as the Transition Pathways *Version 1.1* gas dataset, apart from an assumption of a 90% CO₂ capture rate and a 15% energy penalty (Hammond, Ondo Akwe and Williams, 2011). GHG emissions associated with the distribution of Russian gas were found to be 20 times those from the UK sources (Hammond, Howard and Jones 2013). The latter consequently exhibits very low pipeline GHG emissions, compared to Russian gas. The high impact of Russian gas production and distribution is mainly due to their higher gas leakage in piping, together with longer transmission distances. These upstream GHG emissions also have significance in terms of analysing the three transition pathways, because UK indigenous natural gas supplies are uncertain; notwithstanding the possibility of obtaining shale gas via hydraulic fracturing (or 'fracking'). The 'Reserves to Production Ratio' (R/P) of UK natural gas fields is presently about 5:1, whereas that for the world as a whole is around 63:1 (Hammond and Jones, 2011). Geological estimates of recoverable UK shale gas reserves are, in any case, in their infancy and vary widely.

CCS facilities coupled to fossil-fuelled power plants provide a climate change mitigation strategy that potentially permits the continued use of fossil fuels whilst reducing the CO₂ emissions. However, the present study has indicated (see Table 3) that coal CCS is about 2/3 lower in terms of GHG emissions in comparison with conventional coal-fired plant (without CCS), i.e., a fall from 1.09 to 0.31 kg CO_{2e} per kWh. Thus, CO₂ capture is likely to deliver only a 70% reduction in carbon

emissions on a whole system basis (including both upstream and operational emissions), in contrast to the normal presumption of a 90% saving (Hammond, Howard and Jones, 2013). This brings into question the attractiveness of coal CCS as an environmental proposition. Nevertheless, it is a relatively cheap fuel, which is readily available (from the UK and elsewhere), and provides flexible generation in contrast to new nuclear power (see, for example, Hammond, 2011). Consequently, there is a broader range of factors to consider when selecting new UK power generation capacity. Industrial companies have argued that CO₂ capture facilities may only be built for natural gas power stations, because of the cheaper capital cost compared to a supercritical coal plant (especially as the plant is likely to operate at ‘mid-merit’, rather than baseload). Biomass co-firing with CCS may, of course, mitigate upstream emissions on a full life-cycle basis, due to potential ‘negative emissions’ (Kruger and Darton, 2013): something that needs careful study in the future.

Table 2. Upstream GHG emissions from fossil fuels. [Source: Hammond, Howard and Jones, 2013].

Fuel	defra† GHG Emissions Factor from Combustion of Fuel (kg CO_{2e}/ kWh)	GHG Emissions from Upstream Activities (kg CO_{2e} /kWh)	Resulting Ratio (Increase)
Coal	0.330	0.060	6.5:1 (+18%)
Natural Gas	0.204	0.041	5.0:1 (+20%)

Table 3. Power technologies in ranked order by ‘whole systems’ GHG (upstream plus operational or ‘stack’) emissions. [Source: Hammond and O’Grady, 2014; adapted from Hammond, Howard and Jones, 2013].

Technology (mix)	GHG Emissions (kg CO_{2e}/ kWh_e)
Coal	1.09
Grid Average, 1990	0.90
Grid Average, 2008	0.62
Natural Gas	0.47
Coal CCS	0.31
Natural Gas CCS	0.08
Nuclear	0.02

6.4 RENEWABLE ENERGY SYSTEMS: BUILDING-EMBEDDED SOLAR PHOTOVOLTAIC MODULES

6.4.1 Background

The energy analysis (EA) and environmental life-cycle assessment (LCA) study by Hammond *et al.* (2012) of domestic building-embedded photovoltaic (BIPV) modules as used here as an example of the application of the methods to specific renewable energy technologies. This was part of a broader study of EA, LCA and economic appraisals of a specific BIPV system located in the UK on a 'whole systems' basis. Under the base case the 2.1 kWp BIPV system was estimated to generate 1,720 kWh of electricity per annum. The base case was assumed to be a well installed system (south facing, no shading and with a good inclination) located in the highly populous regions of Southern England. However, in the far South West of Cornwall - England, which has the highest levels of solar insolation in the UK, a well installed 2.1 kWp system may be able to produce up to 2,000 kWh per annum. This is in contrast to Northern Scotland, which has relatively poor levels of solar insolation and may only generate in the region of 1,300 kWh per annum.

6.4.2 Energy Analysis (EA) of BIPV

In order to determine an energy payback period, the embodied energy of the BIPV system was examined by Hammond *et al.* (2012). The quantities of materials required to manufacture a 2.1 kWp BIPV system were analysed. The results demonstrate that the PV cells were responsible for the largest contribution to the system embodied energy (45%); this was not surprising considering that crystalline silicon requires energy intensive manufacturing processes. The BIPV frame, which was manufactured from *Glass Reinforced Plastic* (GRP), represented a large proportion of the energy at 20%. The frame was in the form of a roof tile – it provides the support of the PV laminate and substitutes for the (concrete) roof tiles of the dwelling. This avoids the need for the same quantity of concrete roof tiles (in a new build property). The embodied energy saving from the avoided need for 40 m² of concrete roof tiles was estimated to be almost 1,900 MJ of energy. Other significant contributors included the Tedlar film (13% of embodied energy), the system inverters (two required, total 8% of energy) and the transport at 6% of total embodied energy. Thin-film amorphous PV requires less energy to manufacture than the crystalline technologies, but it also has the lowest cell efficiency, thus requiring a larger rooftop area. This transport includes the impacts of rail, road and shipping of all components from Asia and Europe to the United Kingdom, plus transportation within the UK. A final 200 mile van delivery was assumed in the assessment along with its empty return trip.

The impacts of UK electricity were modelled in *SimaPro* with the *ecoinvent* database using the electricity generation mixture and fuel inputs for the UK production in 2007. The electricity production mix was determined to be made up from 41.9% gas fired electricity, 34.8% coal, 16.1% nuclear, 1.3% wind, 1.3% hydro, 1.2% oil and 3.4% from other resources in the year 2007. It was estimated that the conventional UK electricity generation system (the National Grid network) requires approximately 2.95 units of primary energy (traced to the cradle, LHV) to supply one unit of delivered electricity to a consumer. Accordingly the simple energy payback period and the displaced energy payback period differ by a factor of 2.95 (Hammond *et al.*, 2012). The displaced energy payback period was considered to be the default payback convention for this analysis.

In the base case the simple energy payback would be almost 13.5 years (Hammond *et al.*, 2012). Consequently the system would payback within its assumed 25 year lifetime. The displaced

energy payback period, which was considered as a better indicator, was estimated to be 4.5 years and therefore the (default) energy payback periods were relatively short. Over the 25 year lifetime this corresponds to an energy gain ratio of 4.6, which implies that the system avoids 4.6 times more energy (through generation and displaced electricity) than the embodied energy required in producing the system. These values were favourably within the range found in the literature of 1.7-11.8 (see Hammond *et al.*, 2012).

6.4.3 Environmental Life-cycle Assessment (LCA) of BIPV

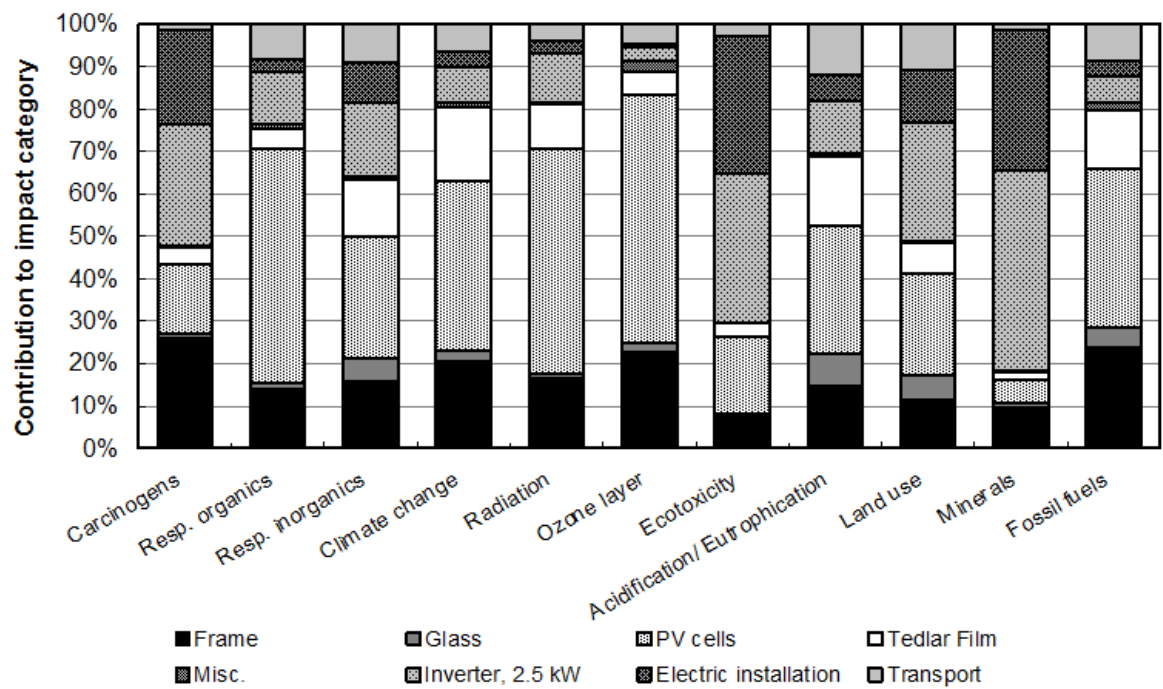


Figure 13. 'Characterised' 2.1kW BIPV system production data (cradle-to-site). [Source: Hammond *et al.*, 2012)]

The corresponding full LCA for the eleven LCA impact categories of Eco-indicator 99 (Goedkoop and Spriensma, 2001) are displayed in Figure 13 as characterised results. The results reveal that the PV cells were responsible for the largest contribution in seven of the 11 impact categories - respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, acidification/eutrophication, and fossil fuels. The two system lifetime inverters were the largest contributors to the remaining four impact categories of carcinogens, ecotoxicity, land use and minerals. Ecotoxicity and minerals were dominated by the inverter and electrical installation (connecting cables and wires); this was a consequence of the copper and steel components within these items. The aggregated impacts of transport (cradle to site) contributed between 1% - 12% of each impact category and on average 6%. The impacts of the delivery to installation site (gate-to-site) were considered to be a relatively minor impact in this case. The data was normalised using the average annual European emissions per capita (EU, 1999).

Greenhouse gas emissions were extracted from the LCA results. The 2.1 kWp BIPV system was estimated to have an embodied carbon of 4,500 kg CO_{2eq} (GWP, 100 year). This may be offset against the avoided impact of roof tiles, which was equal to 217 kg CO_{2eq} and the avoided impact

of 25 years of electricity generation, equal to 26,700 kg CO_{2eq} (Hammond *et al.*, 2012). The net 25 year life-time carbon impact was therefore estimated as a benefit (saving) of 22,400 kg CO_{2eq} – providing a ‘carbon payback period’ of 4 years and a ‘carbon gain ratio’ of 5.0. This case study clearly demonstrates the importance of a system to be analysed over its life-cycle, including the benefits of the electricity it generates (Hammond *et al.*, 2012).

7. LCA-RELATED METHODS: FOOTPRINTING

7.1 CARBON AND ENVIRONMENTAL FOOTPRINT METHODOLOGIES

The use of ecological or environmental footprint (EF) analysis has grown in popularity over recent years, both in Europe and North America. They provide a simple, but often graphic, measure of the environmental impact of human activity: whether or not in the foreseeable future humanity will be able to “tread softly on the Earth” (Hammond, 2000). William Rees used footprint analysis in its basic form to teach planning students for some 20 years (see Wackernagel and Rees, 1996). The terms environmental and ecological footprints are used interchangeably here (as they were previously by Hammond, 2006; Eaton, Hammond and Laurie, 2007; Cranston and Hammond, 2010; and Alderson, Cranston and Hammond, 2012; Hammond and Seth, 2013), although the former expression is preferred. The concept of the ‘carbon footprint’ (CF) is rooted within the framework used to determine the ecofootprint (EF). However, Hammond (2006) noted that a ‘footprint’ would normally be measured in spatial units [such as global hectares (Wackernagel and Rees, 1996; Chambers, Simmons and Wackernagel, 2000)], but that the carbon footprint is typically presented in mass (or weight) units, i.e., kilograms (kg) or tonnes (t). He therefore argued that it should perhaps be termed a ‘carbon weight’ or something similar. Wiedmann and Minx (2008) reviewed various suggestions, including that of Hammond (2007), and then proposed a definition for the ‘carbon footprint’ as including the “total amount of CO₂ emissions that is directly and indirectly caused by an activity”. Great efforts have been made over the past number of years to reach harmonisation in carbon footprint methodology in order to formulate an International standard. Unfortunately this process has proven rather difficult with participating countries unable to reach agreement, and has resulted in a technical specification instead (ISO, 2013). Indeed, many organisations have adopted the use of the term carbon footprint when assessing the carbon dioxide emissions released during various processes or activities, although these are again measured in tonnes of carbon dioxide (Hammond, 2007; Wiedmann and Minx, 2008).

7.2 THE ENVIRONMENTAL IMPLICATIONS OF GLOBAL BIOFUEL PRODUCTION TO 2050

The environmental and carbon footprints of the global biofuel production were recently determined by Hammond and Seth (2013) on both a historic timescale and in accordance with OECD-FAO future projections to 2020. It is adopted here as an example of the relationship between LCA and environmental footprint analysis (EFA). In order to determine the footprints associated with these biofuel resources, the overall environmental footprint was disaggregated into bioproductive land, carbon (CF), embodied energy, materials and waste, transport, and water components. These mainly reflect the impact of *first generation biofuels* (FGB) as second generation technologies will have a relatively low output up to 2020. Hammond and Li (2014) subsequently undertook a related study utilising the projections developed by the IEA as part of their technology roadmap for transport biofuels. These extend out to 2050, and account for the growing impact of *second generation biofuels* (SGB). The EFA resource components were

identified by both Hammond and Seth (2013) and Hammond and Li (2014) and categorised to reflect broad and identifiable policy making categories, which match the consumption of ‘natural capital’ (Eaton, Hammond and Laurie, 2007; Cranston and Hammond, 2010). In the present study, these components were (Simmons, Lewis and Barrett 2000; Eaton, Hammond and Laurie, 2007): bioproductive and built land, embodied energy, materials and waste, transport, and water. The opportunity was taken by Hammond and Li (2014) to critically reappraise the detailed way in which the individual footprint components have been evaluated. In particular, the water footprint of liquid biofuels has been determined using the recent work of Hoekstra and his co-workers (see, for example, Mekonnen and Hoekstra, 2011). That has enabled a cross-comparison of methods for calculating the environmental footprint components, and thereby helping to better determine the relative shares of the different biofuel components out to 2050, including that associated with water consumption.

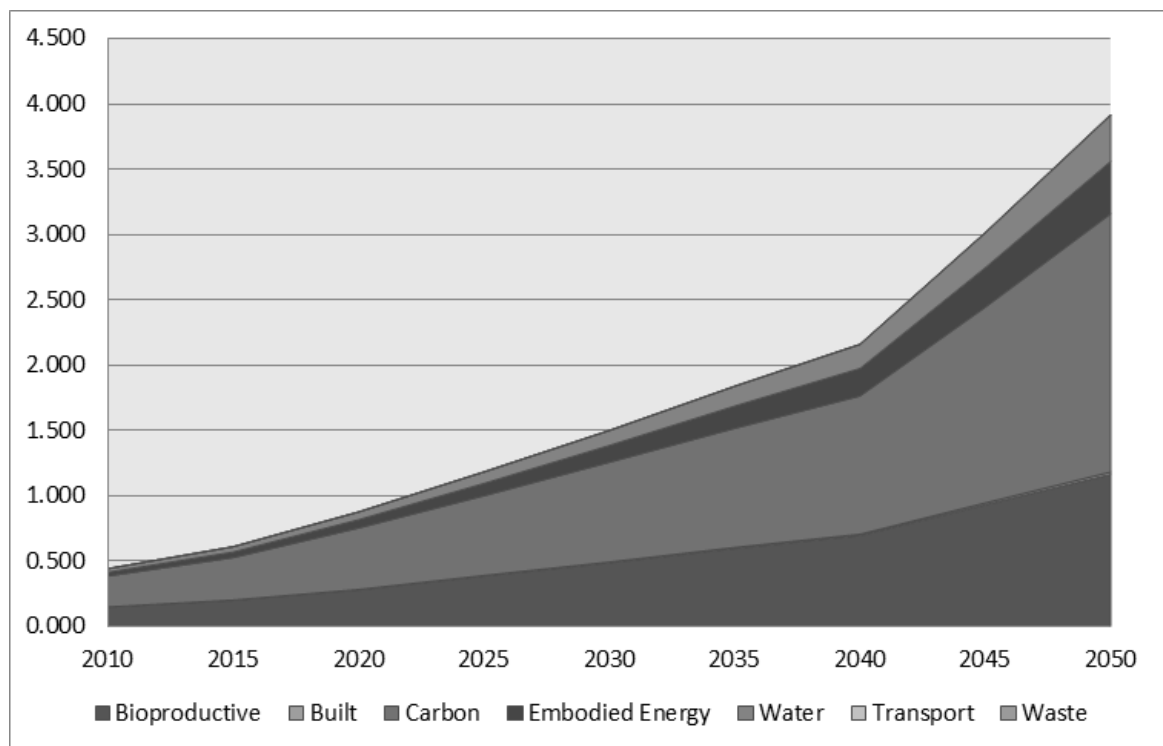


Figure 14. Environmental footprint associated with world biofuel production (billion gha). [Source: Hammond and Li, 2014]]

The total carbon footprint of global biofuels production was estimated by Hammond and Li (2014) to be 0.085 billion (bn) gha for 2010 and with a likely increase to 0.64 billion (bn) gha by 2050 (see Figure 14). Biofuels are limited by their inability to achieve targets for oil-product substitution, without threatening food supplies and biodiversity, and for GHG reductions. Biodiesel produced from vegetable oil was found to have the highest carbon footprint in comparison to other feedstocks. The corresponding estimate for the total global biofuel production environmental footprint was estimated by Hammond and Li (2014) to be 0.29bn gha for 2010 and would grow to 2.57 bn gha by 2050. Bioproductive land use was proved to be the largest footprint component, followed by carbon footprint, embodied energy, and finally water footprint. The footprints of built land, transport and waste were found to account an insignificant amount to the overall EF of global biofuel production.

7.3 Environmental Footprint Analysis (EFA) Versus Environmental Life-Cycle Assessment (LCA)

There has been an increasing interest amongst researchers and practitioners in the relationship and interaction between EFA and LCA (Huijbregts et al., 2008; Castellani and Sala, 2012; Hammond and Seth; 2013). A particularly useful comparison between the two methods has recently been reported by Castellani and Sala (2012) in the context of sustainability assessment of tourism activities in Italy. They drew out the main strengths and weaknesses of the EFA and LCA approaches. The former does not capture the full range of environmental impact categories Castellani and Sala (2012) embracing, for example, damage to resources (resulting from the consumption of fossil fuels and other minerals), damage to ecosystem quality (caused by acidification, eutrophication, ecotoxicity, etc.), and damage to human health (due to human toxicity). On the other hand, EFA provides a useful means of environmental monitoring against a specific physical threshold: the amount of land available. Unlike LCIA, EFA also takes account of limited natural resources or the carrying capacity of the planet (Hammond and Seth; 2013). However, the EFA approach doesn't allow for the multi-purpose use of ecosystems, e.g., to sustain biodiversity, for timber production, and for carbon sequestration. Castellani and Sala (2012) explore the interactions between footprint components, like the seven different components used in the present work, and typical LCA impact categories and associated inventory data. They note that collecting primary data from specific LCA studies of each consumption category will enhance the robustness of EFA. Another recent study by Huijbregts *et al.* (2008) again examined the interrelation between EFA and LCA, but for a range of some 1550 product/process groups consumed in the industrialised global economy. They used the Eco-indicator 99 (EI) LCIA method (Goedkoop and Spriensma, 2001), and found that the EF/EI ratio was constant to within a variation of about $\pm 17\%$. Considerations of this type have led leading EFA practitioners to place the acquisition of better data sources (including those from process and input-output LCA studies) high on their research agenda (Kitzes *et al.*, 2009).

CONCLUDING REMARKS

Techniques of environmental life-cycle assessment (LCA) play an important role in the context of sustainability assessment (Hammond and Winnett, 2006). They are at the heart of methods for the quantifying the direct ecological impacts that are an inevitable side-effect of material 'progress'. Concepts such as the life-cycle of products and processes, and the need for clearly defined system boundaries, are key elements in environmental problem-solving. The present state-of-the-art of (mainly) process-LCA methodology has been critically reviewed in the broad context of sustainability appraisal and its use illustrated via a series of energy sector examples and case studies. These will include specific technologies, such as fossil-fuelled power plants with and without CCS and solar BIPV systems, as well as the 'whole systems' appraisal of national transition pathways. The current strengths and weaknesses of LCA have been identified with energy practitioners and policy analysts in mind as the target audience. Likewise, embodied energy and carbon accounting have been discussed, drawing on the related work of the authors' LCA-linked development of their '*Inventory of Carbon and Energy*' (ICE) database (Hammond and Jones, 2008 and 2011a) that has been widely used by academic researchers and industrialists. Likewise, comparisons were drawn above with related approaches, such as carbon and environmental footprinting (Hammond, 2006; Eaton, Hammond and Laurie, 2007; Cranston and Hammond, 2010; Alderson, Cranston and Hammond, 2012; Hammond and Seth, 2013).

LCA is a useful tool for determining global and regional impacts of a product or system 'from the cradle-to-grave', but is currently unable to incorporate localised impacts (Hammond and Winnett, 2006). However, it is possible that some means to achieve this will be forthcoming in the not-too-distant future. In any event, LCA avoids the examination of products on a close up basis, whereby only one part of the life-cycle is examined. But the results of any LCA study may prove to be 'uncertain', or sensitive to small changes in input data. Quantifying the uncertainties associated with LCA studies (Ciroth, Fleischer, and Steinbach, 2004), particularly those related to bioenergy or biofuels (Hong, 2012; Sills et al., 2012; Yan and Boies, 2013) have become an important element of such assessments. Likewise, it is desirable to undertake a sensitivity analysis in order to reduce the uncertainty in the calculated outputs – weighted contributions the various impact domains (Hammond and Winnett, 2006). This involves employing a systematic procedure to evaluate the effect of changes in key variables. If a small change in some item of input data gives rise to a large change in the resulting life-cycle impact of the product or system being studied, then the LCA is very sensitive to errors or uncertainties in the estimates for that variable. The methods employed in an LCA study only allow for the examination of global and regional impacts, and not local impacts (Hammond and Winnett, 2006; Udo de Haes and Heijungs, 2007). This can obviously bias results. However, as long as there are complementary studies carried out which do take into consideration local impacts, then LCA can still be used to good effect. When employed with other environmental management tools, such as environmental risk assessment, it can form a comprehensive impact assessment package (Hammond and Winnett, 2006).

The initial stages of LCA, those related to scoping and inventory analysis, can be regarded as well-defined and understood. However, the later stages, including the processes of normalisation and weighting are subjective, and many different methods are currently in use. This leads to inevitable problems when the results of impact assessments are interpreted. Nevertheless, LCA is still one of the more scientific, or evidenced-based, of the available environmental management tools. Clearly much more research is needed to refine LCA methods and thereby make them more robust (Hammond and Winnett, 2006). It is critically important that environmental life-cycle assessment studies are peer reviewed (Baumann and Tillman, 2004). This is normally undertaken as part of the refereeing process when the results of studies are submitted for publication in the scientific and technical media. Unfortunately, many industrial studies are not subject to a similar level of rigorous evaluation. There is consequently a need for Government departments and agencies with an interest in the application of LCA techniques over a range of products and systems to establish a "College of Peers" for this purpose (see, for example, Hammond and Winnett, 2006). This could have a very real and near-term effect on improving the reliability of LCA studies.

Commercial LCA software or databases are becoming more readily available. They offer facilities that reduce the barriers for the entry of non-specialists. Access to public domain databases will also reduce the time required to perform an individual study, although it will remain significant in the near term. However, it will still not be a simple task to perform a full or detailed LCA, and the expertise and time needed to undertake a rigorous, whole-life environmental impact assessment must be recognised. There has been much discussion in the industrially-focused literature about the need to devise 'fast track', short-cut, 'streamlined', or simplified methods of life-cycle assessment. Given that full or detailed LCA studies have a number of limitations, it may be argued

(Hammond and Winnett, 2006) that these developments should be discouraged. They are likely to produce misleading results and, as a consequence, damage the credibility of carefully prepared assessments.

ACKNOWLEDGEMENTS

This work is part of a programme of research at the University of Bath on the technology assessment of low carbon energy systems and transition pathways that is supported by a series of UK research grants and contracts awarded by various bodies. In the present context, the first author (GPH) is the Principal Investigator and joint leader a large consortium of nine university partners initially funded via the strategic partnership between *E.ON UK* (the electricity generator) and the UK *Engineering and Physical Sciences Research Council* (EPSRC) to study the role of electricity within the context of '*Transition Pathways to a Low Carbon Economy*' [under Grant EP/F022832/1] over the period 2008 - 2012. The other authors were sequentially funded via this grant in part (CIJ) or wholly (AOG). In 2012 the project was renewed with funded solely from the EPSRC under the title '*Realising Transition Pathways: Whole Systems Analysis for a UK More Electric Low Carbon Energy Future*' [under Grant EP/K005316/1]. The third author (AOG) is currently funded via this grant. First author (GPH) is also a Co-Investigator of the *Biotechnology and Biological Sciences Research Council's* (BBSRC) *Sustainable Bioenergy Centre* (BSBEC), under the '*Lignocellulosic Conversion to Ethanol*' (LACE) Programme [Grant BB/G01616X/1]. All the authors are grateful for the interaction with other members of these research consortia and industrial partners. However, the views expressed here are those of the authors alone, and do not necessarily reflect the views of the collaborators or the policies of the funding bodies.

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4.6 Key Outputs

A full review of the LCA methodology and its application to energy systems has been carried out in this book chapter, accomplishing objective 1 of this thesis. The strength and weakness of energy systems LCA (summarised in Table 5.) were identified to help guide the best use of their results, particularly for energy practitioners and policy analysts.

Table 5. An outline of strengths and weaknesses of LCA for assessing energy systems

Strengths	Weaknesses
<ul style="list-style-type: none">● Holistic environmental appraisal● Established international standards● Procedural transparency● Allows level playing field for comparison● Pinpoints environmental/inefficient hotspots● Springboard for communication	<ul style="list-style-type: none">● Static/snapshot assessments● Variation in assessment due to value choice/ methodological approaches● Only predefined environmental impacts assessed● A target for sustainable activity not specified, only embodied impacts quantified● Data quality● Inaccessible results

Through the examination of a series of energy sector case studies, including the assessment of national electricity systems, the following important considerations for conducting an LCA were deduced:

- LCA is an effective tool for determining global and regional impacts.
- Other environmental management tool must be used to determine local impacts.
- LCA is sensitive to small input changes of key parameters, and may require sensitive analysis to explore this uncertainty.
- First two stages of LCA (scoping and inventory analysis) are well defined and understood, and easily compared between studies, however can be subject to data limitation.
- Impact assessment stage is more subjective and can make cross comparison of studies difficult.
- LCA is a key environmental management tool, but can be subject to misuse in industry.
- LCA could benefit from the development of peer-review national LCA databases.
- Peer review is critical in order to increasing the robustness and credibility of studies.

5 Article II – ‘The implications of upstream emissions from the power sector’

5.1 Journal Paper

G. P. Hammond and Á. O'Grady, 2014. ‘*The implications of upstream emissions from the power sector*’. Proceedings of the Institution of Civil Engineers - Energy, 167 (1), pp. 9-19.

<http://dx.doi.org/10.1680/ener.13.00006>

5.2 Contribution to Research

The life cycle greenhouse gas emissions associated with the *Transition Pathways* version 2.1 were evaluated, and their implications for climate policy were discussed. Particular attention was given to upstream emissions, which have not been fully accounted for by analysis carried out by the CCC and Department of Energy and Climate Change.

This article contributed to the delivery of objective 2 and 3 of this thesis. Firstly, it determines the greenhouse gas (GHG) emissions associated with a power sector of a more electric UK. Secondly, it highlights the environmental significance of ‘upstream emissions’, and explores their technological and policy implications. These upstream emissions arise from the need to expend energy resources in order to extract and deliver fuel to a power station or other users. They include the energy requirements for extraction, processing/ refining, transport and fabrication, as well as methane leakages from coal mining activities, and natural gas pipelines.

This work quantifies the ‘true’ GHG emissions associated with a future UK electricity sector, and identifies a major issue with the current UK decarbonisation approach, particularly with regard to the electricity sector. Since the decarbonisation of the UK electricity sector is a central policy goal to delivering emission reduction [96], it would have serious knock-on implications for the environmental performance for all products and services consuming electricity across the economy. Upstream emissions would remain not fully accounted for, despite current GHG reduction targets being met under current legislation. The collective efforts driven by such policies to meet these targets could therefore, in fact, deliver less meaningful change in the fight against global warming.

The paper was subsequently awarded the 2015 James Watt Medal of the Institution of Civil Engineers (ICE) for best paper in ICE proceedings journal *Energy*.

5.3 The Significance and Originality of the Article

This paper highlights the failure of current legislation, and policy measures, to adequately account for upstream emissions from the power sector, resulting in emissions savings much lower than reported. A life cycle approach was taken in this analysis to quantify the ‘true’ GHG emissions associated with a future UK electricity sector, setting it apart from assessments carried out by the (CCC) and Department of Energy and Climate Change (DECC). These bodies fail to account for upstream emissions fully, including territorial fugitive emissions. The results of this work demonstrate the importance of considering the comprehensive total life cycle GHG impacts of electricity generation to policy-makers when formulating decarbonisation strategies.

5.4 Contribution by Candidate

Main author (generating 66% of content)

The concept of the paper was jointly conceived by both authors. All experimental work, including the modelling and appraisal of the three pathways were performed by the candidate. The drafting of the paper was carried out by both authors. The candidate was responsible for all text relating to experimental work, and contrasting results, with previous assessment and that of CCC and DECC. The candidate also conducted a full critical review of the drafted manuscript, addressing any information gaps and editing of text as required. Furthermore, the candidate also answered and addressed various reviewer comments during the publication process.

5.5 Article II

Proceedings of the Institution of Civil Engineers – Energy

The implications of upstream emissions from the power sector

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Abstract

Upstream environmental burdens arise from the need to expend energy resources in order to extract and deliver fuel to a power station or other users. They include the energy requirements for extraction, processing/refining, transport, and fabrication, as well as methane leakages from coal mining activities – a major contribution – and natural gas pipelines. The upstream carbon dioxide equivalent (CO_{2e}) emissions associated with various power generators and UK electricity transition pathways towards a low carbon future have been evaluated on a ‘whole systems’ basis. CO_{2e} capture facilities coupled to fossil-fuelled plants are shown, for example, to deliver only a 70% reduction in ‘greenhouse gas’ (GHG) emissions (including both upstream and operational emissions), in contrast to the normal presumption of a 90% saving. In addition, the present UK GHG trajectories associated with transition pathways out to 2050 are found to differ significantly from those produced by the British Government’s Department of Energy and Climate Change (DECC) and its independent Committee on Climate Change (CCC). These bodies do not currently account for upstream, ‘fugitive’ GHG emissions. Thus, there will actually remain further emissions upstream that are unaccounted for, even if the current UK CO_{2e} reduction targets are apparently met.

1. Introduction

1.1 Background

Electricity generation contributes a large proportion of the total greenhouse gas (GHG) emissions in the United Kingdom (UK), due to the predominant use of fossil fuel (coal and natural gas) inputs. Indeed, the various power sector technologies [fossil fuel plants with and without carbon capture and storage (CCS), nuclear power stations, and renewable energy technologies (available on a large and small {or domestic} scale)] all involve differing environmental impacts and other risks. However, carbon footprints have become the ‘currency’ of debate in a climate-constrained world. They represent the amount of carbon [or carbon dioxide equivalent (CO_{2e})] emissions associated with a given activity or community, and are generally presented in terms of units of mass or weight [kilograms per functional unit (e.g., $\text{kgCO}_{2e}/\text{kWh}$)]. The UK Government therefore established an independent *Committee on Climate Change* (CCC) under the *Climate Change Act 2008* in order to advise it on progress towards meeting its overall carbon reduction target of 80% by 2050 from heating, power and transport fuels against the 1990 baseline. A new approach was thereby adopted to managing and responding to climate change in the UK, and led to the creation of legally-binding budgets for reducing Britain’s GHG emissions. Thus, the CCC proposed to progressively tighten its second and third carbon budgets (CCC, 2010) to a 37% emissions reduction by 2020 (relative to 1990), followed by reductions from 2010 until 2030 of 46%. In parallel, the CCC advocated deep cuts in power sector emissions through the 2020s (CCC, 2010), with UK electricity generation becoming largely decarbonised by 2030-2040. Anderson *et al.* (2008) have argued that such long-term targets do not have a firm scientific basis, and they examined UK cumulative emission pathways that would be required to help ensure that global mean surface temperatures do not exceed 2 °C above pre-industrial levels. They suggest that industrialised countries must radically and urgently curtail their energy demands (Anderson *et al.*, 2008) in order to stabilise mean surface temperatures in line with the needs for only 2 °C of global warming.

A consortium of partners from nine British university institutions was established (Hammond and Pearson, 2013) with research funding provided under the auspices of a strategic partnership between *E.ON UK* (the electricity generator) and the UK *Engineering and Physical Sciences Research Council* (EPSRC) to study ‘transition pathways’ to a more electric future for the United Kingdom of Great Britain and Northern Ireland (UK). They adopted the Dutch transitions approach (see, for example, Rip and Kemp, 1998; Geels, 2002; Verbong and Geels, 2010) and a time horizon out to 2050. The UK team devised three energy transition pathways that were distinguished by their governance structures: driven by the market, central government intervention, and local community initiative respectively. A framework was developed whereby the descriptions or ‘narratives’ associated with these pathways underwent technological elaboration with quantitative underpinning provided by a range of different economic and technical models (Hammond and Pearson, 2013). In addition, the ‘whole systems’ energy and environmental performance of these UK electricity transition pathways was evaluated by Hammond *et al.* (2013) on a ‘life-cycle’ basis. Both energy analysis and environmental life-cycle assessment (LCA) were employed to constitute a ‘whole systems’ approach to the UK energy system (Figure 1).

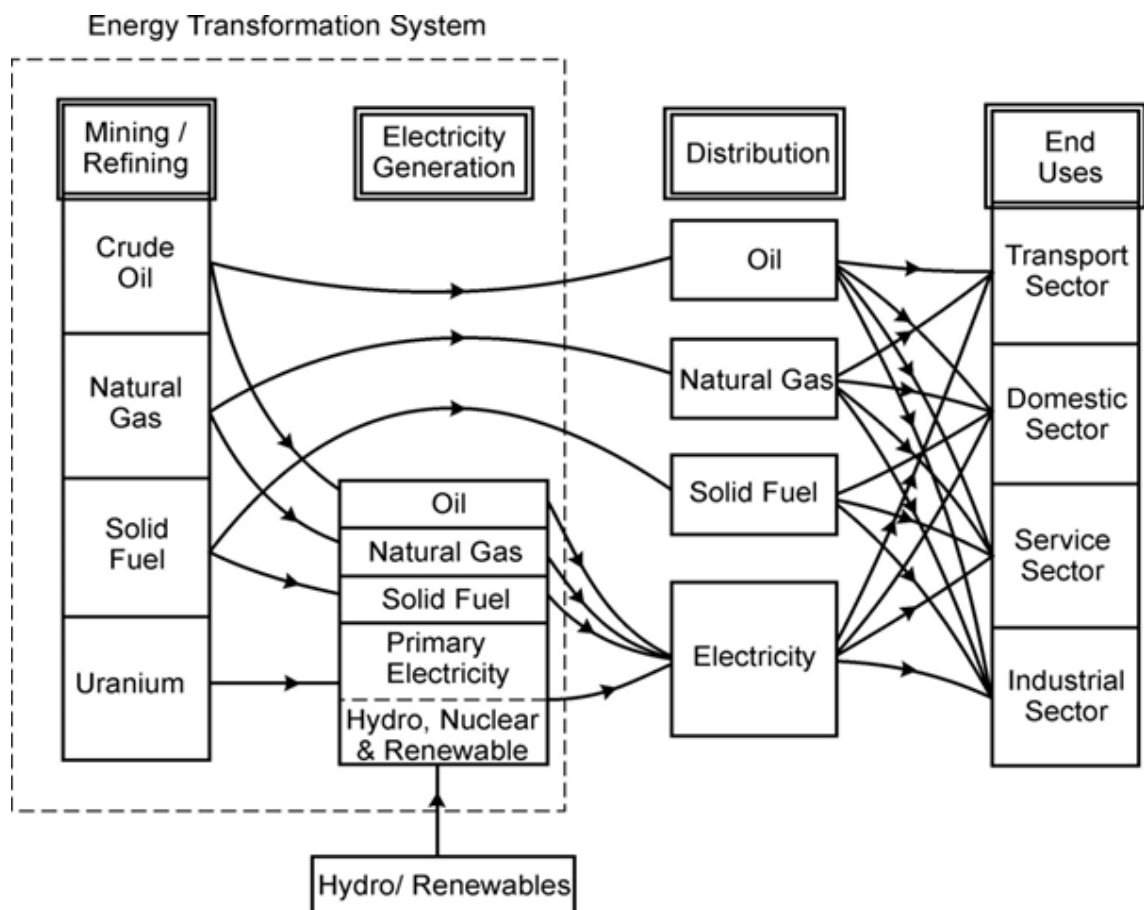


Figure 1. A simplified representation of the UK energy system. [Source: Hammond, 2000].

Energy analysis required estimates of the energy outputs of the power generators during use, and the energy requirements for their construction and operation. In contrast, LCA studies produce estimates of a wider range of pollutants or wastes released into the environment as a consequence of the power network. Upstream environmental burdens arise from the need to expend energy resources in order to deliver, for example, fuel to a power station. They include the energy requirements for extraction, processing/refining, transport, and fabrication, as well as methane leakage that occur in coal mining activities – a major contribution – and from natural gas pipelines. Thus,

‘whole system’ GHG emissions = upstream GHG emissions + operational GHG emissions

where the ‘operational’ or ‘stack’ emissions are those directly associated with the combustion of fossil fuels within power stations. These whole system emissions amount to those related to the ‘*Energy Transformation System*’ as defined by Slessor (1978): see again Figure 1 (Hammond, 2000). The impact of upstream, particularly ‘fugitive’, emissions on the carbon performance of various low carbon technologies [such as large-scale combined heat and power (CHP) plants and CCS] and the pathways distinguish these findings, and differ significantly, from those of other UK analysts.

A few months after the publication of the study by Hammond *et al.* (2013), the *Committee on Climate Change* launched a report that contained (amongst other things) the findings of its own study of life-cycle emissions of low carbon and conventional energy technologies, including

various power generators¹ (CCC, 2013). This indicated that low carbon power generation technologies, such as nuclear power and renewable energy technologies, all exhibit a significant emissions savings in comparison to their fossil fuel equivalents on a life-cycle basis. They found that fossil fuel (coal and natural gas) power plants with CCS provide much lower emissions than conventional stations without CO₂ capture, but are both were much higher than those associated with low carbon technologies. Coal CCS also displayed considerably greater emissions than that arising from gas CCS. Consequently, the CCC argued that CCS stations should only be employed as part of a portfolio low carbon power generators, with preference given to gas CCS and, potentially, biomass CCS. In quantitative terms these findings are similar to those found by Hammond *et al.* (2013) and in the present study. However, the CCC have not as yet accounted for upstream, fugitive emissions in their modelling studies of UK CO_{2e} emission trajectories over their various carbon budget periods or out to the ultimate 80% reduction target set for 2050.

1.2 The Issues Considered

Three transition pathways for a more electric future out to 2050 (Foxon *et al.*, 2010) have been evaluated here in terms of their life-cycle energy and environmental performance. These are similar to the estimates made by Hammond *et al.* (2013) relating to *version 1.1* of the pathways, but the present research examined the most recent *version 2.1*. This second iteration of the pathway narratives (Foxon, 2013) was used to identify the changes that might be expected in how end-users consume electricity according to the logic of each pathway: driven by the market, central government intervention, and local community initiatives respectively. The *Transition Pathways* consortium's *Technical Elaboration Working Group* (Hammond and Pearson, 2013) then quantified the resulting power demands to meet domestic, commercial, industrial and transport, energy end-uses (see Figure 1), as well as the consequent supply requirements and generator capacity out to 2050. The present study has therefore been based around the appraisal of energy use and CO_{2e} emissions associated with *version 2.1* of the transition pathways. An integrated, life-cycle approach has again been used (Allen *et al.*, 2008; Hammond *et al.*, 2013). Thus, the techniques of both energy analysis and environmental life-cycle assessment (LCA) were applied on a 'whole systems' basis. The focus here is on the implications of upstream, particularly fugitive, CO_{2e} emissions in relation to the power generators (including the consequences for the adoption of CCS facilities in the power sector) and the modelling of future UK electricity projections out to around 2050. This work forms part of an ongoing research effort aimed at evaluating and optimising the performance of various sustainable energy systems (see, for example, Allen *et al.*, 2008; Hammond, 2011; Hammond *et al.*, 2011; Hammond *et al.*, 2013) in the context of transition pathways to a low carbon future for the UK (Alderson *et al.*, 2012; Foxon *et al.*, 2010).

2. Energy Analysis and Carbon Accounting on a Life-Cycle Basis

2.1 Methods

In order to determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial system (Allen *et al.*, 2008; Hammond and Winnett, 2006; Udo de Haes and Heijungs, 2007). This idea is based on the First Law of Thermodynamics, that is, the principle of conservation of energy, or the notion of an energy balance applied to the system. It leads to the technique of First Law or 'energy' analysis, sometimes termed 'fossil fuel accounting', which was developed in the 1970s in the aftermath of the oil crisis [see, for example, Roberts (1978) or Slesser (1978)]. There are several different

¹ For which the first author (GPH) was a member of the relevant CCC peer review panel, alongside industry representatives.

methods of energy analysis (see Figure 2); the principal ones being statistical analysis, input-output table analysis, and process analysis (Allen *et al.*, 2008; Roberts, 1978; Slessor, 1978). The first method is limited by the available statistical data for the whole economy or a particular industry, as well as the level of its disaggregation. Statistical analysis often provides a reasonable estimate of the primary energy cost of products classified by industry. However, it cannot account for indirect energy requirements or distinguish between the different outputs from the same industry (Roberts, 1978). The technique of input-output table analysis, originally developed by economists (Hammond and Jones, 2008), can also be utilised to determine indirect energy inputs. This approach is constrained only by the level of disaggregation that is available in national input-output tables. Process energy analysis is the most detailed of the methods, and is usually applied to a particular process or industry; requiring process flow-charting. More recently, hybrid methods using a combination of I/O and process energy analysis have been developed (see, for example, Hammond *et al.*, 2013).

Energy analysis preceded LCA and as such they share much of the same fundamental methodology. In order to evaluate the environmental consequences of a product or activity the impact resulting from each stage of its life-cycle must be considered. This led to the development of ecotoxicology, or a study of the harmful effects of releasing chemicals into the environment, and a range of analytical techniques that now come under the 'umbrella' of life-cycle assessment. The aim of the LCA is often to identify opportunities for environmental improvement by detecting the areas with the most significant impacts (Hammond *et al.*, 2013). In the present study, the focus has been on carbon accounting, rather than the wider range of environmental burdens examined by Hammond *et al.* (2013), who determined 17 separate impact indicators, as well as a tentative 'single score', aggregate LCA metric.

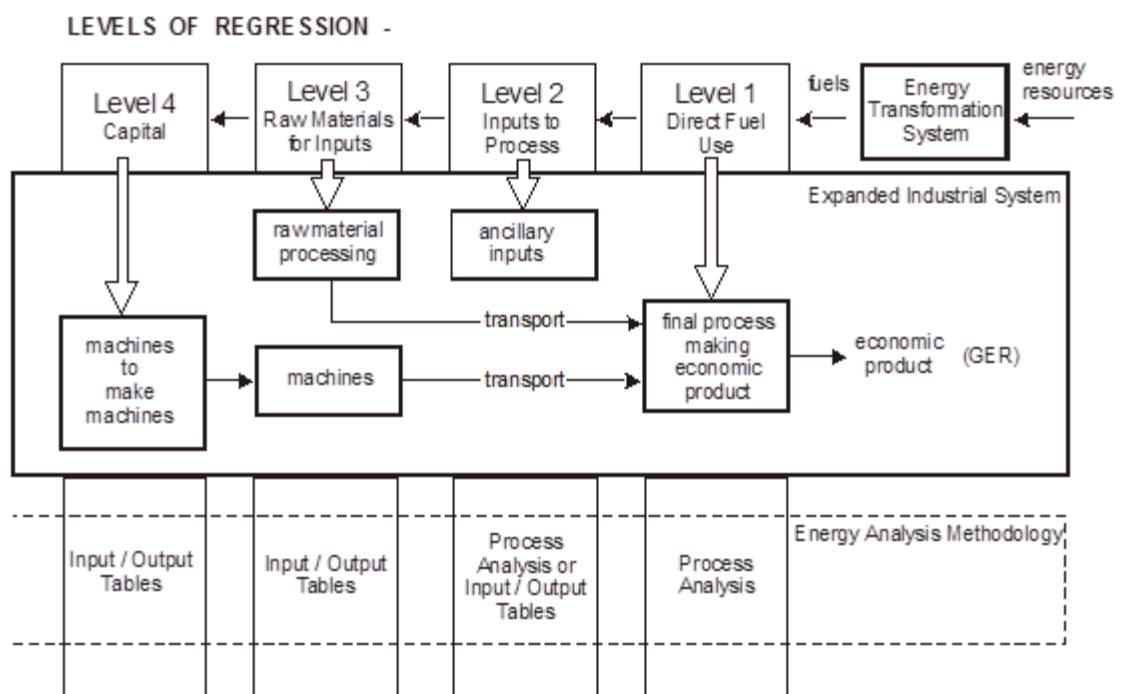


Figure 2. Schematic representation of the energy analysis process. [Source: Allen *et al.*, 2008; adapted from Slessor, 1978].

2.2 System Boundaries

The system boundary in energy analysis (EA) should strictly encompass the energy resource in the ground (e.g., oil in the well or coal at the mine – the ‘cradle’), although this is sometimes taken as the national boundary in practice (see again Figure 1). Analysis is ideally performed over the entire life-cycle of the product or activity, ‘from cradle to grave’. Different ‘levels of regression’ may be employed (Slessor, 1978), depending on the extent to which feedback loops are accounted for, or the degree of accuracy desired (see Figure 2). Thus, the sum of all the outputs from this system multiplied by their individual energy requirements must be equal to the sum of inputs multiplied by their individual requirements. The process consequently implies the identification of feedback loops, such as the indirect, or ‘embodied’, energy requirements for materials and capital inputs. In a full LCA, the energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole life-cycle; again ‘from cradle-to-grave’ (see Heijungs *et al.*, 1992; Udo de Haes and Heijungs, 2007). However, detailed ‘end-of-life’ (i.e., decommissioning and waste recycling) information is rarely available on which to carry out a complete analysis. Life-cycle analysis often involves activities that are geographically diverse; that is, the energy and material inputs to a product or service may be drawn from any continent or geo-political region of the world.

Embodied energy and carbon appropriate to the various UK power generators were determined by Hammond *et al.* (2013) using proprietary LCA software tools and databases, together with the ‘Inventory on Carbon and Energy’ (ICE) [developed at the University of Bath (Hammond and Jones, 2008 and 2011)]. Embodied energy and carbon emissions of the various technologies are based on real life data compiled from current power plants. In the case of more novel technologies (e.g., wind and wave), proxy datasets have been tailored based on leading studies of this technology. These impacts have been averaged per kWh over the entire lifecycle of the plant to allow both current and future plants to be compared on a like by like basis at any given time. Current technology data has been assumed for future plants due to the uncertainty in technology improvements into the future.

‘Embodied energy’ is here defined as the total primary energy consumed from direct and indirect processes associated with power production and within a system boundary defined as ‘cradle to gate’ (Hammond and Jones, 2011). This includes upstream activities from material extraction (quarrying/mining), manufacturing, transportation, fabrication processes, and construction of the power plant. The most significant upstream impact is due to fugitive emissions arising from methane leakages that occur in coal mining activities and from natural gas pipelines. In the present study, the downstream boundary is effectively taken as the point of electricity end-use: mainly in the home, by the commercial service provider, or in the factory. Similarly, ‘embodied carbon’ is the sum of fuel-related carbon emissions (i.e., embodied energy which is combusted, but not the feedstock energy which is retained within materials) and process-related carbon emissions (Hammond and Jones, 2011). Adding operational or ‘stack’ emissions effectively results in all the emissions right through to the delivery of electricity to the consumer. This might then be thought of as a ‘cradle to consumer (or end-user)’ system boundary or ‘whole systems’ emissions.

3. Upstream Emissions from Power Plants

The operational (direct or stack) emissions associated with the combustion of fuels are compared with GHG emission associated with upstream coal and natural gas activities in Table 1. This data indicates the magnitude of the difference between direct combustion and upstream emissions. Such fugitive GHG emissions, for example, arise from the production and transport of natural gas.

They imply that the measures advocated by the CCC for decarbonising the UK economy, viewed by some as challenging, are actually likely to be not stringent enough. The resulting impacts are highly variable depending upon source of gas: whether, for example, they come from UK natural gas fields or are imported into Britain from the Russian Federation. The gas CCS dataset interrogated here is the same as the Transition Pathways *version 1.1* gas dataset, apart from an assumption of a 90% CO₂ capture rate and a 15% energy penalty (Hammond *et al.*, 2011). GHG emissions associated with the distribution of Russian gas were found to be 20 times those from the UK sources (Hammond *et al.*, 2013). The latter consequently exhibits very low pipeline GHG emissions, compared to Russian gas. The high impact of Russian gas production and distribution is mainly due to their higher gas leakage in piping, together with longer transmission distances. These upstream GHG emissions also have significance in terms of analysing the three transition pathways, because UK indigenous natural gas supplies are uncertain; notwithstanding the possibility of obtaining shale gas via hydraulic fracturing (or ‘fracking’). The ‘Reserves to Production Ratio’ (R/P) of UK natural gas fields is presently about 5:1, whereas that for the world as a whole is around 63:1 (Hammond, 2011). Geological estimates of recoverable UK shale gas reserves are, in any case, in their infancy and vary widely.

CCS facilities coupled to fossil-fuelled power plants provide a climate change mitigation strategy that potentially permits the continued use of fossil fuels whilst reducing the CO₂ emissions. However, the present study has indicated (see Table 2) that coal CCS is about 2/3 lower in terms of GHG emissions in comparison with conventional coal-fired plant (without CCS), i.e., a fall from 1.09 to 0.31 kg CO_{2e} per kWh. Thus, CO₂ capture is likely to deliver only a 70% reduction in carbon emissions on a whole system basis (including both upstream and operational emissions), in contrast to the normal presumption of a 90% saving (Hammond *et al.*, 2013). This brings into question the attractiveness of coal CCS as an environmental proposition. Nevertheless, it is a relatively cheap fuel, which is readily available (from the UK and elsewhere), and provides flexible generation in contrast to new nuclear power (see, for example, Hammond, 2011). Consequently, there is a broader range of factors to consider when selecting new UK power generation capacity.

Table 1. Upstream GHG Emissions from Fossil Fuels [Source: Hammond *et al.*, 2013].

Fuel	defra† GHG Emissions Factor from Combustion of Fuel (kg CO_{2e} per kWh)	GHG Emissions from Upstream Activities (kg CO_{2e} per kWh)	Resulting Ratio (Increase)
Coal	0.330	0.060	6.5:1 (+18%)
Natural Gas	0.204	0.041	5.0:1 (+20%)

†Data Source: The UK Department for Environment, Food and Rural Affairs (defra) - UK National Atmospheric Emissions Inventory (NAEI) maintained by Ricardo-AEA [see <http://naei.defra.gov.uk/>].

Table 2. Power Technologies in Ranked Order by ‘Whole Systems’ GHG (Upstream plus Operational or ‘Stack’) Emissions [Source: adapted from Hammond *et al.*, 2013].

Technology (mix)	GHG Emissions (kg CO_{2e} per kWh_e)
Coal	1.09
Grid Average, 1990	0.90
Grid Average, 2008	0.62
Natural Gas	0.47
Coal CCS	0.31
Natural Gas CCS	0.08
Nuclear	0.02

Industrial companies have argued that CO₂ capture facilities may only be built for natural gas power stations, because of the cheaper capital cost compared to a supercritical coal plant (especially as the plant is likely to operate at ‘mid-merit’, rather than baseload). Biomass co-firing with CCS may, of course, mitigate upstream emissions on a full life-cycle basis, due to potential ‘negative emissions’ (Kruger and Darton, 2013): something that needs careful study in the future. CHP – whether coal or natural gas fired – uses one energy input, but two energy outputs: heat and power. Carbon emissions therefore need to be allocated or partitioned on some basis between these so-called ‘co-products’. This can be achieved on the basis of either energy, exergy, or economic value (Hammond *et al.*, 2013). These different treatments will yield varying results for this technology and the various future projections. CHP is a ‘carbon-heavy’ technology that is likely to provide a large contribution to the UK carbon profile going forward towards 2050. CHP contributes substantially in all three pathways, especially in under a decentralised, ‘civil society’ driven regime (termed the *Thousand Flowers* pathway) as can be seen in Figure 3.

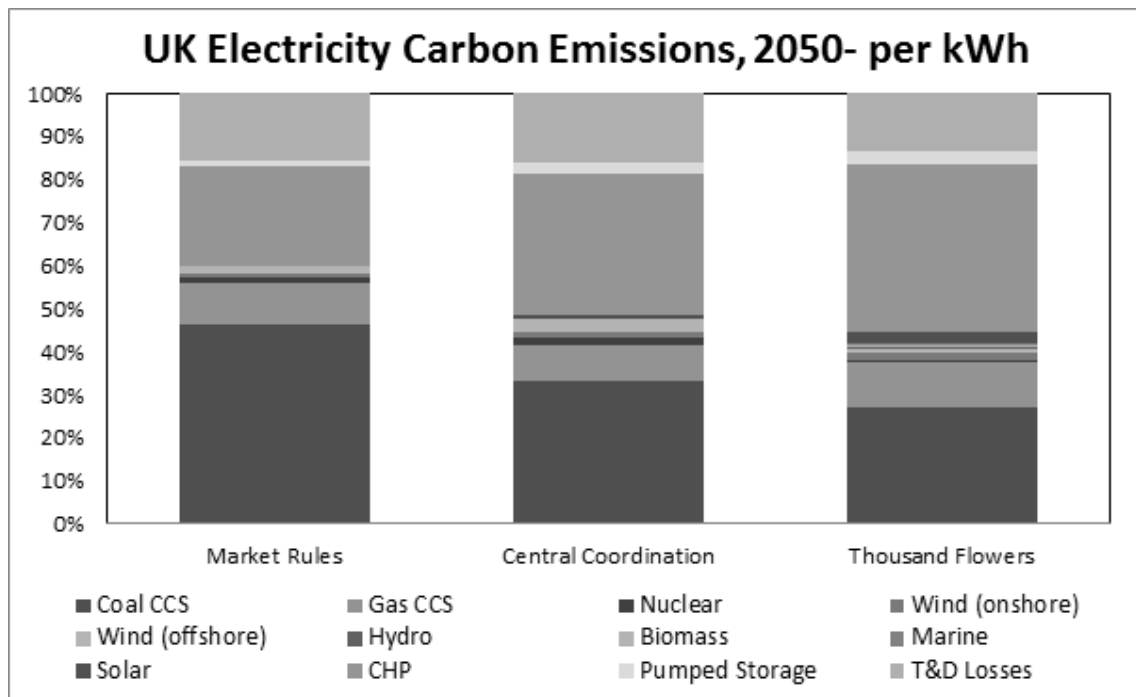


Figure 3. Power Generator Shares of the UK ‘Whole Systems’ Carbon Intensity (kg CO₂e/kWh) in 2050 under each of the Three Transition Pathways – Version 2.1.

4. Upstream Emissions from More Electric Transition Pathways

A number of reputable studies have been undertaken in recent years that yield low or zero carbon energy scenario sets for the UK. These include those produced by the British Government’s *Department of Energy and Climate Change* (the DECC 2050 Calculator; see DECC, 2010), the *UK Energy Research Centre* (the UKERC Energy 2050 Project; see Skea *et al.*, 2010), the *Tyndall Centre for Climate Change Research* (Mander *et al.*, 2008), and the *Centre for Alternative Technology* (the *Zero Carbon Britain 2030* Project; see CAT, 2010). They all enable insights to be drawn regarding the realism of each projection, and reflect a range of aspirations from those wishing to achieve 2050 carbon reduction targets (80% in the case of DECC and UKERC), to that of completely decarbonising Britain by 2030 (CAT). The five Tyndall decarbonisation scenarios (Mander *et al.*, 2008) were focused on an earlier 60% carbon reduction target for 2050, although they employ a distinctive ‘backcasting’ approach generated and reviewed with the aid of stakeholders. On the other hand, the DECC 2050 Calculator is basically an engineering-based, Excel spreadsheet model that is open source and arguably transparent. The tool permits users to select their own combination of technologies to achieve an 80% reduction in GHG emissions by 2050, whilst ensuring that energy supply and demand are balanced. The UKERC Energy 2050 Project (Skea *et al.*, 2010) involved a four-scenario core set that was underpinned by a cost-optimisation model (UK MARKAL). It took “an eclectic approach to scenario building” with a backcasting dimension to achieve a combination of UK energy resilience and climate change mitigation. In contrast, the *Zero Carbon Britain 2030* Project (CAT, 2010) examines how to radically ‘power down’ UK heat and electricity demand – what they viewed as ‘high carbon living’ - through the adoption of a combination of new technology, efficient design across the economy and motivating behavioural change, while ‘powering up’ the use of renewables to supply the residual energy requirements. The selection of an appropriate energy scenario or pathways set is rather arbitrary for the current purposes of illustrating the implications of upstream emissions on the power sector. The focus of the present study is therefore on the three pathways developed by the *Transition Pathways Consortium* (funded via

the E.On-EPSRC strategic partnership). It consisted of UK engineers, social scientists, policy analysts, and innovation specialists, and included both the present authors.

The *Transition Pathways* Consortium sought to develop and explore three ‘transition pathways’ towards a UK low carbon electricity system (Foxon *et al.*, 2010; Hammond and Pearson, 2013), to understand the changing roles of large and small ‘actors’ in the dynamics of these transitions, and to learn from the successes and failures of past transitions. They have focused on the choices and actions needed to ‘get there from here’, and on the analysis of the pathways’ technical, socio-economic and environmental implications. An innovative, arguably robust, and ‘whole systems’ evidence base was developed that is distinctive from those devised elsewhere in the UK energy research community in its focus on governance structures. The pathways are not predictions or roadmaps; rather they are a way of imaginatively exploring future possibilities, to inform proactive and protective decision making and enhance the potential for building consensus towards common goals.

An initial set of transition pathways for a UK low carbon energy system were developed by applying three main steps (Foxon *et al.*, 2010): (1) characterising the existing energy regime, its internal tensions and landscape pressures on it; (2) identifying dynamic processes at the niche level; and (3) specifying interactions giving rise to or strongly influencing transition pathways. They were devised via stakeholder workshops (involving UK energy researchers, industrialists, and policy advisers and decision-makers), a narrative descriptive of each pathway, and their subsequent technical elaboration. Stakeholder workshops were employed by the consortium to distinguish the logics of three core sets of actors: driven by the market, central government intervention, and local community initiative respectively. Consequently, the three transition pathways were named *Market Rules* (MR), *Central Co-ordination* (CC) and *Thousand Flowers* (TF); each being dominated by a single group’s logic.

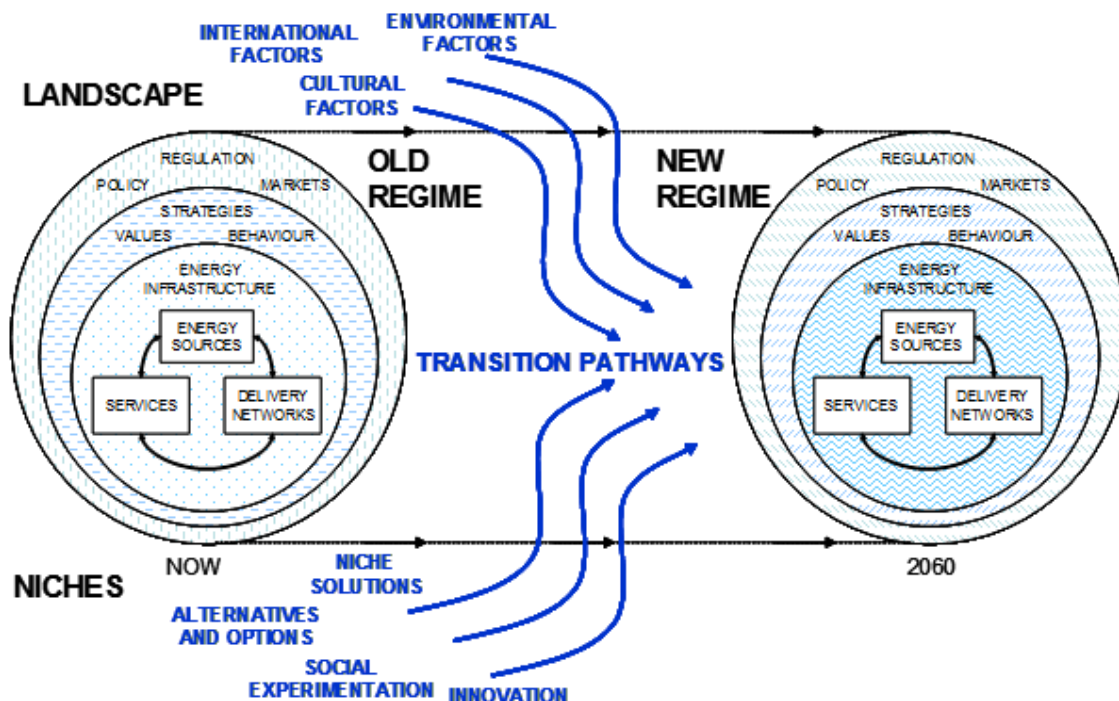


Figure 4. Possible transition pathways and the factors that influence them. [Source: The Transition Pathways Consortium (Foxon *et al.*, 2010)].

Hammond and Pearson (2013) summarise the development and high-level analysis of the *version 2.1* transition pathways set, in order to explain their key features and the distinctiveness and value of the approach; the approach builds *inter alia* on approaches originally devised by Dutch researchers (e.g., Geels, 2002; Rip and Kemp, 1998; Verbong and Geels, 2010). Thus, the consortium applied a multi-level perspective for analysing socio-technical transitions, based on interactions at and between three levels: *niche innovations*, *socio-technical regimes*, and *macro-landscape pressures* [see Figure 4 (Foxon *et al.*, 2010)].

The development of the UK transition pathways has undergone several iterative loops. Earlier whole systems appraisal by Hammond *et al.* (2013) related to *version 1.1* of the pathways. However, a second iteration of these pathways was performed in order to investigate the weaknesses of that version in terms of technical feasibility, electric grid enhancement needs, social acceptability, energy and environmental performance, and also in light of outcomes for stakeholders' workshops (Foxon, 2013). Based on the logic of the three pathways, using a bottom up approach, the change of energy use was determined, and the demand by sector was modelled (Barton *et al.* 2013). The progression of the electricity mix required to meet the demand while adhering to the logic of the given pathway, was then projected (Barnacle *et al.*, 2013). *Version 2.1* also enabled the pathways to be updated in order to incorporate further stakeholder inputs and developments in UK energy policy.

In the study by Hammond *et al.* (2013) *version 1.1* of the pathways (Foxon *et al.*, 2010) was evaluated in terms of their energy and environmental performance. Subsequently, following the development of *version 2.1* of the pathways, a similar study was carried out and is reported here that adopted the same methodology. Earlier studies of the carbon and environmental footprints of low carbon UK energy futures (by, for example, Alderson *et al.*, 2012) suggest that refinements of the technical elaboration or quantification of the pathways are unlikely to make significant differences to their environmental impacts reported. In this present study, similar trends were observed in both iterations, although *version 2.1* suggests greater decarbonisation by 2050. There are many GHG emissions, and each has a different potency. Each of a basket of six 'Kyoto' gas is normalised relative to the impact of one unit of carbon dioxide (IPCC, 2007); the main contributor to climate change. They are typically expressed in terms of 'carbon dioxide equivalents', with units of kgCO_{2e}; where 'e' denotes equivalents. Projected 'whole systems' carbon emissions (i.e., operational or 'stack', plus upstream emissions) from the UK *Electricity Supply Industry* (ESI) [Mt CO_{2e}] under all three *version 2.1* transition pathways over 1990-2050 are shown in Figure 5. In contrast, the power generator shares of the UK carbon intensity (kg CO_{2e}/kWh_e) in 2050 under each of the *version 2.1* pathways are illustrated in Figure 3. The coal CCS share of emissions is seen to fall significantly from the MR pathway through CC to its lowest value for TF. Its dominance is largely replaced by CHP generation. Nuclear power plays the more significant role in CO₂ reductions under the CC pathway. Large-scale renewables have a major influence by 2050 under the CC pathway and, particularly, the TF pathway [see again Figure 3]. Similar trends were seen in *version 1.1* with minor changes made to key technologies, especially in TF pathway. Coal CCS has less dominance under *version 2.1*, while gas CCS, wind and nuclear power share increased in both MR and CC pathways. In contrast, the role of coal CCS, gas CCS and nuclear power was reduced in TF pathway, and replaced mainly by CHP.

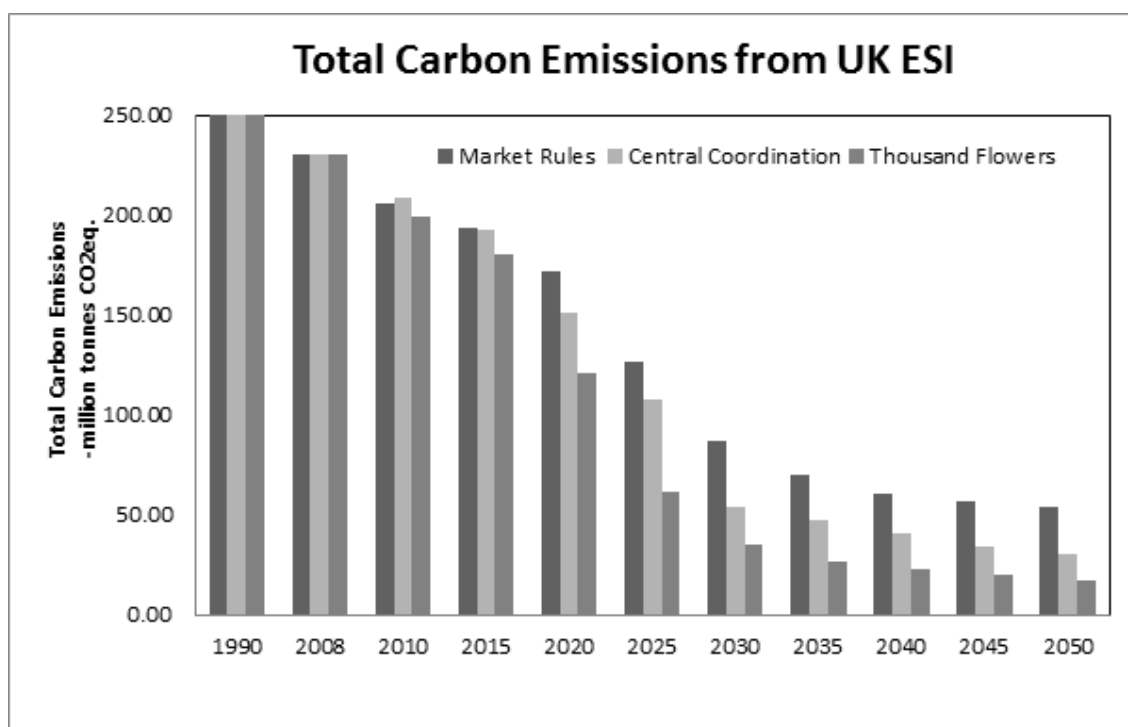


Figure 5. Projected UK ‘Whole Systems’ Carbon Emissions from the Electricity Sector (Mt CO_{2e}) 1990-2050 under the Three Transition Pathways - Version 2.1.

The present *version 2.1* transition pathways (see, for example, Figure 5) suggest that, taking account of upstream emissions, there might actually be a fall in carbon emissions from the UK power generation sector of some 31-51% by 2020, 65-86% by 2030, and 78-93% in 2050. The lower figures relate to the MR pathway, whilst the higher ones are associated with the *Thousand Flowers* pathway. The CCC advocated deep cuts in power sector operational emissions through the 2020s (CCC, 2010), with UK electricity generation largely decarbonised by 2030-2040. In contrast, the present transition pathways (see again Figure 5) projections indicate that the UK ESI could not be fully decarbonised by 2050 on the ‘whole systems’ basis employed in the current study (see Figure 1). This is because the present estimates take account of upstream, fugitive GHG emissions, whereas the projections by bodies like the CCC and *Department of Energy and Climate Change* (DECC) do not. Nevertheless, the transition pathways suggest that the ESI will be able to bear a significant share of the overall 80% carbon reduction target by 2050. The CCC analysis suggests that their projections would lead to average operational emissions from generation falling to around 50 gCO_{2e}/kWh_e by 2030. In contrast, the present MR pathway (Figure 3) indicates that ‘whole system’ emissions from the UK ESI are likely to only fall, accounting for upstream emissions, to ~202 gCO_{2e}/kWh_e by 2030 and ~105 gCO_{2e}/kWh_e by 2050. Even the least impactful pathway TF, indicates emissions falling to only ~108 gCO_{2e}/kWh_e by 2030 and ~53 gCO_{2e}/kWh_e by 2050.

5. Concluding Remarks

An integrated approach was recently used by Hammond *et al.* (2013) to assess the impact of *version 1.1* of three UK transition pathways (Foxon *et al.*, 2010; Hammond and Pearson, 2013). They employed both energy analysis and LCA, applied on a ‘whole systems’ basis: from ‘cradle-to-consumer’. This highlighted the significance of upstream (particularly fugitive) emissions, in contrast to power plant operational or ‘stack’ emissions, as well as their technological and policy implications. The findings were reinforced by the carbon and environmental footprint analysis of Alderson *et al.* (2012), who examined the environmental impacts associated with UK power generation based on historic data and a set of three alternative energy scenarios out to 2050. They

found that their projections indicated that the UK ESI could only be near-decarbonised by 2050 under various low carbon scenarios. This is because their environmental footprint estimates also took account of upstream emissions (i.e., those associated with what is termed the ‘embodied energy’ footprint component). Here the most recent UK transition pathways (*version 2.1*) have been appraised; again on a whole systems basis.

The emissions reductions achieved from power plants fitted with CO₂ capture technology may not be as high as many figures suggest. There is no doubt that having a CCS plant is better than having one without CCS, but in order to get realistic estimates of how attractive they are going to be, account must be taken of upstream emissions. Incorporating the emissions from mining (and the ‘fugitive’ methane emissions that escape as a result), as well as the average penalties for processing, transportation and facility construction, combined with the emissions once the feedstock is combusted, it was found that the CO₂ capture rate was significantly lower than those typically presumed. Thus, the study by Hammond *et al.* (2013) indicated that that coal CCS is about two-thirds lower in terms of greenhouse gas emissions in comparison with conventional coal-fired plant (without CCS), a fall from 1.09 to 0.31 kg CO_{2e} per kWh. CO₂ capture facilities are therefore likely to deliver only about a 70% reduction in carbon emissions on a whole system basis (including both upstream and operational emissions), in contrast to the normal presumption of a 90% reduction. The failure to include upstream emissions not only impacts the environmental performance of electricity as demonstrated here, but many goods and services across the UK. Decarbonisation policies may lead to shift in practices and production that might produce unintended negative environmental effects upstream that remain unaccounted.

The present results for life-cycle CO_{2e} emissions from various power generators, and the earlier ones of Hammond *et al.* (2013), are similar to those obtained from the recent study commissioned by the *Committee on Climate Change* (CCC, 2013). The CCC argue as a result that CCS power stations should only be employed as part of a portfolio low carbon power generators (CCC, 2013), with preference given to gas CCS and, potentially, biomass CCS. Obviously, a 70% reduction in CO₂ emissions due to power plant CCS is a significant gain in terms of climate change mitigation, although Hammond *et al.* (2013) noted that this technology may not be all that much more attractive than unabated natural gas. This is especially the case when one takes into account the health and environmental impacts of coal-linked pollution, like particulate matter and mercury. The findings of Hammond *et al.* (2013) have attracted international media interest, including in the USA [see, for example, the report by the journalist Tamar Hallerman in the online ‘*GHG Monitor*’: <http://ghgnews.com/index.cfm/study-total-emissions-reductions-from-ccs-likely-70-not-90/>].

Finally, if governments are serious about meeting stringent GHG emissions reduction targets, like the aim to cut CO₂ emissions in the UK to 80% below 1990 levels by mid-century, they will need to account for the fact that emissions savings stemming from particular technologies may not be as high as many predict. Neither the UK Government’s *Department of Energy and Climate Change* (DECC, 2010) nor its independent *Committee on Climate Change* (CCC, 2010) currently account fully for upstream, fugitive GHG emissions in their projections of CO₂ pathways towards the legally binding emissions reduction target out to 2050. They neglect, in particular, methane leakages that occur in coal mining activities – a major contribution – and from natural gas pipelines. The CCC, for example, have not as yet accounted for upstream emissions in their modelling studies of UK CO_{2e} emission trajectories over their various carbon budget periods or out to the ultimate 80% reduction target set for 2050. If the UK Government is genuine in its desire to meet its challenging CO_{2e} reduction targets, then it will be necessary to account for

upstream, fugitive emissions from power plants. Otherwise, there will actually remain further emissions upstream that are unaccounted for, even if the current UK CO₂ reduction targets are apparently met. Thus, upstream emissions provide a drag on our ability to deliver on meaningful global warming targets in the UK and the wider world.

Acknowledgements

This work is part of a programme of research at the University of Bath on the technology assessment of low carbon energy systems and transition pathways that is supported by a series of UK research grants and contracts awarded by various bodies. In the present context, the first author (GPH) is jointly leading a large consortium of university partners funded by the UK *Engineering and Physical Sciences Research Council* (EPSRC) entitled '*Realising Transition Pathways: Whole Systems Analysis for a UK More Electric Low Carbon Energy Future*' [under GrantEP/F022832/1]. The second author (AO'G) is wholly funded via this grant. Both authors are grateful for the interaction with other members of the Consortium (and its predecessor) made up of participants from nine UK universities. However, the views expressed here are those of the authors alone, and do not necessarily reflect the views of the collaborators or the policies of the funding body.

The authors' names are listed alphabetically.

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5.6 Key Outputs

The full life cycle GHG emissions of the power sector were determined for three transition pathways to a UK low carbon future; delivering objective 2 of this thesis. It was found that these pathways could deliver a reduction in GHGs emissions of 31-51% by 2020, 65-86% by 2030 and 78-93% by 2050, where the lower figures related to *Market Rules* pathway, and the higher figures to the *Thousand Flowers* pathway. Whole life cycle emissions were seen to range from 105gCO₂e/kWh for *Market Rules* in 2050, to 53gCO₂e/kWh for *Thousand Flowers* in 2050.

Market rules pathway was heavily dependent on both coal and gas carbon capture and storage [97] to deliver GHG reductions, and accounted for much of the upstream emissions which refrained this pathway from fully decarbonising by 2050. Large-scale renewables were a key technology in both the *Central Coordination* and *Thousand Flowers* pathway. Nuclear power was responsible for large GHG reduction, and coal and gas CCS to a lesser extent, under *Central Coordination*; whilst, nuclear power, and coal and gas CCS, had only minor influence on the GHG performance of the *Thousand Flowers* pathway. Instead, a large growth in large-scale renewables was backed up by a greater dominance of combined heat and power. Despite all pathways failing to become completely decarbonised by 2050, these pathways suggest that the electricity sector can still bear a share of the overall 80% GHG reduction target by 2050.

This assessment asserted that the emissions saving of switching to certain technologies, such as coal and gas CCS, and combined heat and power (CHP), would not deliver the same GHG savings as predicted by the government. Currently only direct (or 'stack') emissions are assessed by both the UK's government's Department of Energy and Climate Change, and its independent Committee on Climate Change. These bodies fail to account for upstream emissions fully, including territorial fugitive emissions. This analysis highlights the importance of including upstream emissions (fulfilling objective 3 of this thesis), and incorporating life cycle thinking in policy-making.

6 Article III - ‘Linking storylines with multiple models: an interdisciplinary analysis of the UK power system transition’

6.1 Journal Paper

E. Trutnevyte, J. Barton, Á. O'Grady, D. Ogunkunle, D. Pudjianto, E. Robertson, 2014. ‘*Linking storylines with multiple models: an interdisciplinary analysis of the UK power system transition*’. Technological Forecasting and Social Change, 89, 26-42.

<http://dx.doi.org/10.1016/j.techfore.2014.08.018>

6.2 Contribution to Research

The combined use of quantitative models and qualitative storylines are widely employed in energy scenarios to facilitate more robust investigation of the future systems [98-100]. Both approaches bring their respective advantages to future-oriented research. Qualitative storylines provide a ‘bigger picture’ of a wider transformation, and include softer elements, such as governance and behaviour change which cannot yet be modelled. In contrast, quantitative models take a narrower focus, but supply a rigorous technical grounding to developments within the scenarios. Despite the wide application of both storylines and models, little research had been conducted on best methodological approaches to linking both methods. A process was proposed in this paper to link a detailed storyline with multiple models and appraisal techniques, to develop more coherent and robust scenarios. The *Central Coordination* (the government-led pathway) storyline was used to illustrate this new approach. Eight models and appraisal techniques were linked to the storyline in this analysis, including the energy and environmental assessment of the pathways carried out by the candidate.

A new concept called ‘*the landscape of models*’ was developed to enable the cross-comparison of models, to map their depth, breadth and principal area of expertise. Through harmonising assumptions, the models outputs were contrasted with qualitative statement from the storyline to assess area of divergence between the two methods, and identify any inconsistencies. This process provided an internal review of both methods, highlighting areas requiring improvement.

This work was part of an ongoing research effort between consortium members (including the candidate), to facilitate and enhance multidisciplinary and interdisciplinary modelling approaches. This paper meets objective 4 of this thesis, by using these improved modelling techniques to better inform the future development of the UK electricity sector.

6.3 The Significance and Originality of the Article

This journal represents the first structured attempt to link a storyline with a diverse range of models, which have different spatial, temporal and disciplinary foci, in an effort to produce more enhanced and coherent scenarios. Similar to the *Realising Transitions Pathways* consortium,

interdisciplinary projects in energy, climate change and other technology- and environment-related studies are growing in order to fully tackle these complex issues. This approach provides guidance to these projects on developing cross-scale scenarios by linking storylines with multiple models.

6.4 Contribution by Candidate

Co-author (generating 10% of content)

The concept of this analysis arose during *Realising Transition Pathways* [101] consortium workshops. Consortium members wished to harmonise results from the consortium's research to improve the development of collaborative interdisciplinary findings. The candidate participated in a workshop held with co-authors to develop, and perform the analysis as presented in this paper. The candidate drafted all text relating to energy and environmental assessment of the central coordination pathway. A critical revision of the drafted manuscript was carried out by the candidate, and then also a final review of the completed paper.

6.5 Article III

Linking storylines with multiple models: an interdisciplinary analysis of the UK power system transition

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Abstract

State-of-the-art scenario exercises in the energy and climate change fields argue for combining qualitative storylines with quantitative modelling. This paper proposes an approach for linking a highly detailed storyline with multiple, diverse models. This approach is illustrated through an interdisciplinary analysis of the increased role of the government in shaping the UK power system transition until 2050. The storyline, called *Central Co-ordination*, is linked with insights from six power system models and two appraisal techniques. First, the storyline is ‘translated’ into harmonised assumptions that can be used by these models. Then, the concept, called the landscape of models, is introduced. This landscape helps to map the key fields of expertise of individual models. The storyline is then assessed based on the results of the models and appraisals. It is shown that the storyline is important for transmitting information about the governance arrangements and the choices of key actors. However, the storyline is fragile in light of modelling results and can be improved on this basis. To the best of the authors’ knowledge, this is the first structured attempt to bring together such diverse range of models for fleshing out a storyline. The proposed approach could thus be useful for other interdisciplinary analyses.

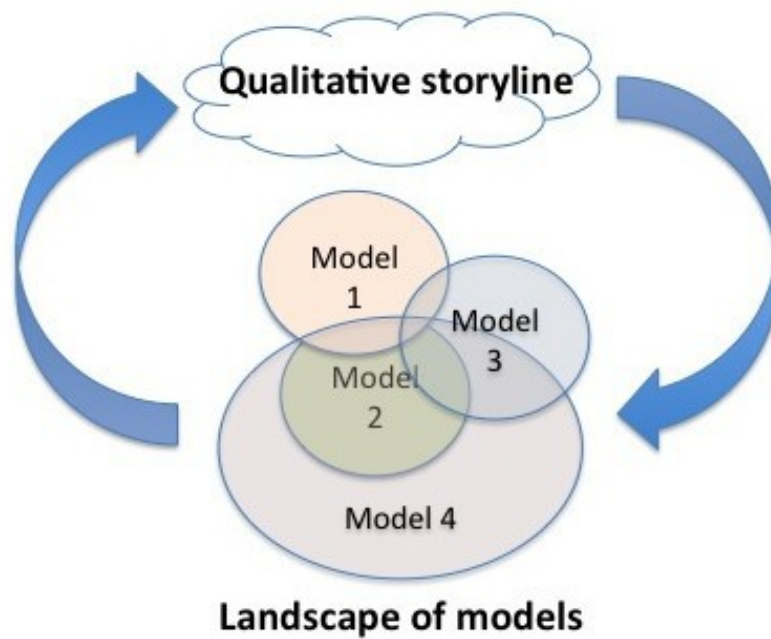
Keywords

Scenarios, storylines, quantitative models, energy, climate change, interdisciplinary, transition pathways

Highlights

- Linking qualitative storylines with multiple, diverse quantitative models
- Landscape of models for mapping the fields of expertise of individual models
- Interdisciplinary analysis of the UK power system transition until 2050

Graphical abstract



1. Introduction

Scenario exercises in energy, climate change and other technology- and environment-related studies are based on qualitative storylines, quantitative models or, often, on a combination of both [1-6]. Storyline-based scenarios are expressed as qualitative narratives that in length may range from brief titles to very long and detailed descriptions. Examples of such scenarios are the Tyndall decarbonisation scenarios [7, 8], the CLUES decentralised energy scenarios [9] or the energy visions in Switzerland [10, 11]. The value of such storylines is threefold [2, 4, 12-14]. First, when these storylines are developed through engagement of experts and stakeholders, they combine multiple perspectives and sources of expertise [2]. They may lead to novel and creative ways of thinking about the future that go beyond modelling insights. Second, storylines are key for communicating the results of scenario exercises. Due to their qualitative nature, they are accessible and memorable to a broad range of audiences. When developed through stakeholder engagement, they are likely to be accepted, supported and used more often [15]. Third, storylines represent a much broader picture than quantitative models and encapsulate a number of softer and subtler aspects that cannot yet be modelled [16]. Storylines thus can form the input assumptions to the quantitative models and embed these models into a bigger picture [17, 18]. However, storylines have two key limitations. First, storylines alone at times may be detached from reality as even experts can have a limited understanding of whether a particular storyline is feasible [10, 11, 15]. Second, as storylines are developed by combining multiple views of experts and stakeholders, they can be considered biased, not reproducible and not transparent [2]. Despite the current research on formal techniques for developing better storylines [5, 12, 19-21], these limitations still remain.

Quantitative models-based scenarios are produced by a single or multiple models, such as in the ADAM [22], Energy Modelling Forum [23], Low Carbon Society modelling [24] and NEEDS [25] projects. The key strength of these scenarios is that they satisfy the inherent need for numeric values in the technology- and environment-related fields [2, 10, 14, 15]. Models are based on the actual data, laws of physics, principles of economics and state-of-the-art knowledge about the technology and environmental processes. Thus, peer-reviewed, transparently documented models provide rigorous, internally consistent scenarios. However, models can address only a limited number of aspects, such as technology, economic, environmental aspects. But they still have difficulty in capturing the afore-mentioned softer and subtler aspects. The key research tendencies are towards developing more detailed models and including softer aspects, such as behaviour and governance, into models [17, 26]. Yet,

even better models alone can hardly offer the breadth and engaging nature of the storyline-based scenarios.

In light of these strengths and weaknesses of storylines and quantitative models, state-of-the-art scenario studies argue for combining them [1-6]. Many recent scenario exercises already have the elements of both: storylines include numbers, while modelling outputs are described in short qualitative narratives. Several scenario exercises explicitly combine the storylines and the quantitative models in an iterative manner [6, 10, 11, 27-29]. Examples of these include key international scenario exercises: the integrated climate change scenarios of the Intergovernmental Panel on the Climate Change [30, 31], the scenarios of ecosystem services in the Millennium Ecosystem Assessment [32] and of the global environment in the Global Environmental Outlook [33]. This approach is thus also used for analysing the UK power system transition pathways until 2050 in the Realising Transition Pathways (RTP) project.

The RTP project is a continuation of the original Transition Pathways project. Grounded in the conceptual framework of socio-technical transitions [34], the original Transition Pathways project combined historical and future- oriented, technical, environmental and social perspectives into an interdisciplinary analysis of the future UK power system transition [35-37]. Three transition pathways—*Central Co-ordination*, *Market Rules* and *Thousand Flowers*—were elaborated in this preceding project [37, 38]. Every of the three transition pathways encapsulated a storyline (or a narrative), its quantitative representation (a scenario) as well as a range of additional analyses, such as the analyses of branching points and actors' choices and power system modelling. In the succeeding RTP project, a structured process was envisioned and implemented for linking these original storylines with the insights from multiple models, available in the RTP project. This process is reported here for one of these storylines, namely *Central Co-ordination*.

Despite the fact that a combination of storylines and quantitative models starts emerging as an established practice in the technology- and environment- related fields [1-6], existing literature runs short in providing methodological insights for how to link such storylines with multiple models. First, the RTP storylines are very detailed (four to five pages) and numerous additional assumptions are needed to 'translate' them into model parameters. Second, there are six power system models and two appraisal techniques available in the project. They are very diverse and differ in their disciplinary perspective (technical feasibility, economic or environmental appraisal), model objective, the parts of the power system addressed and the format of inputs and outputs. This diversity is valuable because the storylines can be addressed from

multiple angles, but it is challenging to relate such diverse models to each. Thus, a new approach had to be developed for linking such detailed storylines with multiple, very diverse models. To the best of the authors' knowledge, this is the first structured attempt to bring together such diverse range of models for fleshing out a storyline. Although it is the first attempt, it is highly relevant. There is a growing number of similar interdisciplinary projects, like the RTP project [39]. It can be expected that many of these projects will attempt to develop scenarios by linking storylines with multiple models. Pulling together a number of existing models is a challenge in itself, in addition to their linking with the storylines. This paper provides some methodological insights for organising these processes.

This paper is laid out as follows: Section 2 provides the essential background about the UK power system, the RTP project, the *Central Co-ordination* storyline and the models and appraisals; Section 3 introduces the process used for linking the storyline with the multiple models; Section 4 discusses the results and the process; Section 5 concludes.

2. The case of the UK power system transition

2.1. UK power system and the RTP storylines

In the 1990s the UK underwent a major process of liberalisation of its power market and privatisation of its companies [40, 41]. With about three quarters of power produced in fossil fuel-based plants, this market-led approach came under significant pressure in the last decade due to growing climate change concerns. The UK government undertook several key interventions. In 2008 the UK adopted the Climate Change Act, supported by all major political parties, which sets a legally binding target to cut the country's greenhouse gas emissions by 80% by 2050 as compared to the emission levels of 1990. In line with [42], the major decarbonisation of the power sector, together with substantial levels of electric heating and transport, are seen as the key measures to reach this target. However, replacement of the aging coal and nuclear power plants and significant investments in transmission and distribution requires massive investment. An increased deployment of renewable energy sources raises concerns over their intermittency and, thus, supply security. Therefore, this decarbonisation challenge does not stand alone and is a part of the so-called energy policy 'trilemma' of decarbonisation, affordability and supply security [37, 43]. The Energy Bill, released in 2012, and especially its part on Electricity Market Reform, attempts to mediate between these three corners of the 'trilemma' [44]. The Energy Bill aims to set a policy framework for the power system transition that meets the 'trilemma.'

In light of these developments, the RTP project aims to shed light on the potential transition pathways of the UK power system until 2050. Three transition pathways were developed: *Central Co-ordination*, *Market Rules* and *Thousand Flowers* [37, 38]. Compared to other scenario exercises in the UK [7-9, 45] and elsewhere, these pathways are novel because they include storylines that specifically focus on the role of governance ‘logics’ and multiple actors in actively shaping the power system transition. Traditionally in scenario studies, storylines are used for representing key uncertainties such as population growth, technological development and others, c.f. [30-33]. The RTP storylines explicitly focus on the uncertainty around governance ‘logics’ and the choices of actors.

The process of developing of these three storylines is described in detail in [37]. In brief, the first version of the storylines was developed in the original Transition Pathways project in a stakeholder workshop in 2008. The technical feasibility, social acceptability and the sustainability of the first version of the storylines were then interrogated in further workshops with experts and key stakeholders, who represented energy companies, policy-makers and non-governmental organisations. This interrogation led to the revised version 2.1 of the pathways, which is currently the latest version. The complete storylines are available online at [38] and shorter summaries are published in [37]. Every storyline consists of four to five pages of qualitative description, a list of key risks for the realisation of the specific storyline and an overview table. Afterwards, a Transition Pathways Technical Elaboration Working Group was set up from the experts in the project in order to assign a quantitative representation for every storyline. This quantitative representation shows the numeric values of the total UK power demand and the power generation mix until 2050 [37]. This process, however, was partly informed by insights from three models, but none of these models were informed by economic considerations [37]. In the succeeding RTP project, there are more models available, of which some include the economic considerations. Therefore, a more structured process was undertaken for linking the storylines with insights from multiple models. In so doing it will show how iteration between storylines and models can fruitfully enhance the process of developing and analysing the broader transition pathways.

2.2. The Central Co-ordination storyline

The *Central Co-ordination* storyline, analysed in this paper, is one of the three storylines of the RTP project: *Central Co-ordination*, *Market Rules* and *Thousand Flowers*. These storylines respectively picture three ideal types of governance ‘logics’ in the UK power system (Figure 1): government, market and civil society ‘logics’. The different groups of actors are assumed to frame their view and enrol the other actors

into their 'logic' [37]. In the case of the *Central Co-ordination* storyline, the central UK government argues for the dominant role of the direct co-ordination and the national government actors to deliver the energy policy goals. In the *Market Rules* storyline, the market actors argue that the energy 'trilemma' is best achieved by the large power companies and other market actors, freely interacting with the policy framework. The investment, made by the large power companies on the basis of investment return (including carbon price effects), available knowledge, regulatory framework and incentives set by the government, will determine the power system transition. The *Thousand Flowers* storyline argues that civil society shall take an active role in delivering the low-carbon transition as small-scale solutions through community-led initiatives and energy service companies (ESCOs). The key recent developments in the UK power sector are described as a hybrid between the *Central Co-ordination* and the *Market Rules* storylines [46]. Since the power market liberalisation in 1990s, the market 'logic' has been dominating in the UK, but the influence of the government 'logic' is increasing in the recent years, especially after the adoption of the legally binding emissions target. The *Central Co-ordination* storyline is therefore chosen for in-depth analysis in this paper.

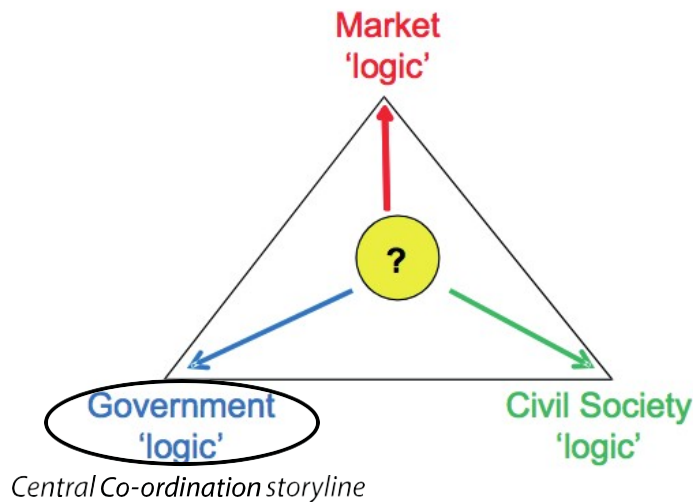


Figure 1. The three ideal types of governance 'logics' in the UK power system transition. Source: J. Burgess and T. Hargreaves. The figure is reproduced from [37].

In the *Central Co-ordination* storyline, the central UK government will actively shape the power system transition through the establishment of Strategic Energy Agency. This agency will issue tenders for tranches (central contracts) for particular types of low-carbon generation and develop 'technology push' programmes for low-carbon technologies. In order to promote UK industry, the agency will primarily support those technologies where the UK has a potential to become a global leader: marine renewables (offshore wind, wave and tidal power), carbon capture and storage

(CCS) and electric vehicles. This strong government commitment will underwrite the investment risks for the large power companies. These companies will invest according to the government's plans and deliver the transition, dominated by large-scale power generation. The government will focus on removing the system-wide blockages, such as the lack of transmission capacity, planning issues, supply chains and skills. As a result, the emission mitigation target of 80% by 2050, as compared to the year 1990, will be achieved. As noted, civil society will remain a relatively passive player in this storyline. Initially, only non-behavioural measures of demand response will be used, such as increased efficiency standards for appliances and newly built buildings. Later, with the increased industrial and climate benefits, the interventions on the lifestyles and behaviour will be undertaken by the government. The key risks, identified in the storyline for the realisation of this transition, are the (i) technical and economic feasibility of CCS, (ii) public opposition to costly low-carbon investment due to increased household expenditure, (iii) little effort to incentivise behaviour change of the energy users. The more detailed storyline is also provided in Table 2, where this storyline is linked with six models and two appraisals. In addition to the qualitative narrative, the *Central Co-ordination* storyline was already assigned an initial quantitative representation (Figure 2), developed in an iterative process by the Transition Pathways Technical Elaboration Working Group.

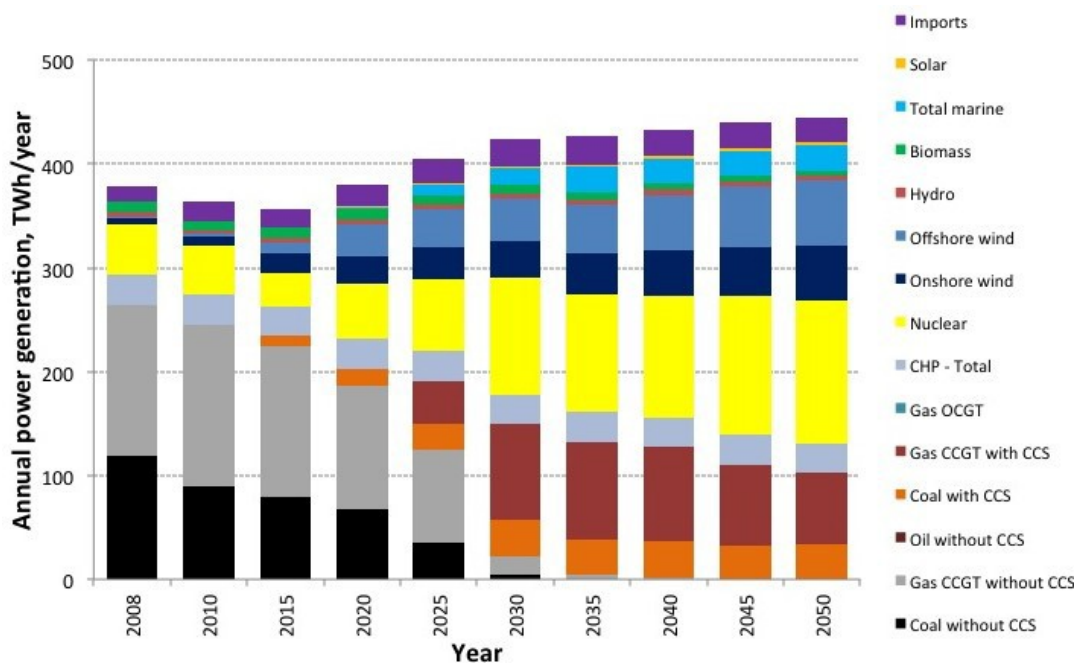


Figure 2. The initial quantitative representation of the *Central Co-ordination* storyline. Source: Transition Pathways project. The figure is reproduced from [37].

2.3. Eight models of the RTP project

This section describes the six power system models and two appraisal frameworks (also called ‘models’) that were linked in this paper to the *Central Co-ordination* storyline. These models are very diverse and this diversity is a strong point as there is not a single best model or methodology that encapsulates all the relevant aspects [16]. The RTP leadership envisioned a multi-model analysis, expecting that this analysis, rather than results of a single model, has potential to provide a broader spectrum of insights.

The eight models used are (in the order of the breadth of the power system boundaries):

Demand: The energy demand model, developed at the University of Surrey, is a bottom-up model of the UK power demand in the domestic and non-domestic sectors. Due to its highly disaggregated structure, the influence of a range of parameters can be modelled, such as the energy service levels, user practices, choices of appliances, building fabric, fuels, deployment of distributed generation and others. The model is based on the synthesis of existing estimates [47-49] and the assumptions from the *Central Co-ordination* storyline.

FESA: The Future Energy Scenario Assessment model [50, 51], developed at the Loughborough University, is a single-year UK power generation and demand model, incorporating one-hour time step for dispatch modelling and using real weather data of temperature, wind speeds, wave height and solar radiation. The model develops scenarios on the basis of the *Central Co-ordination* storyline and technical feasibility constraints.

D-EXPANSE: The D-EXPANSE model (Dynamic version of EXploration of PAtterns in Near-optimal energy ScEnarios), developed at the University College London, has the structure of a bottom-up power system model. In addition to the cost optimisation, D-EXPANSE systematically explores the maximally different near-optimal pathways [15, 29, 52, 53]. In this way, D-EXPANSE aims to open up the understanding of the fundamentally different ways how the UK power system could evolve. By allowing the deviation from the cost-optimal pathway, D-EXPANSE also explores the structural uncertainty around the concept of rationality and cost-optimisation. The D-EXPANSE model has been validated by comparing its outputs with the results of existing, well-established whole system models and cost estimates for the UK [53].

EconA: The Economic Appraisal (EconA), conducted by University College London, aims to evaluate the investment needed, costs, benefits and the related risks and uncertainties of the transition pathways. The EconA is an appraisal technique; it takes the quantitative representation (Figure 2) of the *Central Co-ordination* storyline and appraises it. In this paper, the Econ A is also considered as a model in a broader sense.

BLUE-MLP: The BLUE-MLP model (Behaviour Lifestyles and Uncertainty Energy model with Multi-Level Perspective on transitions) is a probabilistic systems dynamic simulation that explores the uncertainties due to sector- and actor- specific behavioural elements [54, 55]. These behavioural elements include market heterogeneity, intangible costs and benefits, hurdle rates, replacement and refurbishment rates and demand elasticities. In addition, the model links these behavioural uncertainties with the multi-level perspective to transitions [34], where landscape (government decisions and the international context), regime (the current UK power system structure and its regulation) and niche innovations (lifestyle influenced changes in demand) interact with each other.

EEA: The Energy and Environmental Appraisal (EEA) is conducted by the University of Bath [56, 57]. It aims to evaluate the ‘whole system’ (from cradle to gate) greenhouse gas emissions and other environmental impacts, such as human toxicity, particulate matter formation and agricultural land occupation. Similarly to the EconA, the EEA framework is a model in a broader sense as it appraises the *Central Co-ordination* storyline, based on its initial quantitative representation (Figure 2).

HESA/UK+: This is a combination of the Hybrid Energy System Analysis tool (HESA) and the Strathclyde UK+ models that were developed at the University of Strathclyde [58-60]. Strathclyde UK+ model contains all the information for the transition pathways scenarios with spatial disaggregation (17 onshore, five offshore zones and 39 connections) of generation, storage, transmission and distribution. It is linked to the HESA model, which cost-optimises the system, based on the energy hub concept [61, 62]. The national power demand and generation mix are used as input assumptions.

HAPSO: The Holistic Approach to Power System Optimisation model (HAPSO) is developed at the Imperial College London. It is a bottom- up, cost-minimisation model that determines the optimal generation, energy storage, transmission, and distribution network infrastructure requirements and their associated cost to achieve the objectives: economic efficiency, security, sufficient system controllability. The model optimises simultaneously the long-term investment and short-term operating

decisions including hourly generation dispatch, Demand Side Response, storage cycles, and power exchanges taking into account the impact of decisions across all sectors in power system [63]. The UK power system is embedded in the European power system including UK, Ireland and continental Europe and thus allows for modelling of the power exchange across these regions.

Understanding and mapping the breadth and depth of the expertise of every individual model in a multi-model analysis is challenging, especially given such a diverse set of models. Here this mapping is attempted in two ways. First, Table 1 lists the key characteristics of the models. Based on that, the **key field of expertise** is identified for every model. This key field of expertise is the types of insights that a particular model analyses in most depth, as compared to the other seven models. This concept of the key field of expertise thus appreciates the distinct value of every model in this multi-model analysis.

Second, Figure 3 provides a visual mapping of the eight models; this map is called the **landscape of models**. It aims to summarise the information about the breadth and depth of the analysis, done by every model, and to show how these fields of expertise overlap between the models. This mapping is done on the basis of the parts of the power system addressed (demand; generation; dispatch, demand response and storage; transmission and distribution; and interconnectors with Europe) and other thematic considerations addressed by the model (analysis of the maximally different alternatives; uncertainty; behaviour and heterogeneity of actors; economic considerations; environmental considerations; and spatial disaggregation). These thematic considerations are specific to this analysis and might differ for analyses with other sets of models. The depth of analysis is defined in three categories: detailed modelling (the key field of expertise), stylised modelling and exogenous assumptions only.

Both Table 1 and Figure 3 help to show that the eight models, used in this analysis, cover a broad spectrum of insights. To some extent these models overlap. If models overlap, then they can validate each other and help cross-checking the results. Every model, however, always has at least one area where it outperforms the other models in depth or breadth. And this shows that there is no single best model that covers all the aspects in depth; all of the eight models are useful as none of them alone covers all the relevant aspects in depth. The concept of the key field of expertise of every model is thus especially useful here. It shows which conclusions of which model shall be prioritized over the conclusions of other models. The conclusions that are derived from the key fields of expertise of a specific model shall be weighted more than the conclusions on the same topic of the other models.

Table 1. Summary of the eight models (model versions as of April 2013)

Model	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
Spatial scope	UK, single region	UK, single region	UK, single region	UK, single region	UK, single region	UK, single region	UK, 17 onshore and 5 offshore regions	UK, 5 regions Europe, incl. UK, Ireland and continental Europe
Finest temporal resolution	1 year	1 hour	5 years	1 year	1 year	1 year	1 year	1 hour
Parts of the power system addressed								
--Power demand	Total demand; Demands by users, energy services, end-use equipment	Total demand; Demands by users, energy services, end-use equipment	Total demand	Total demand	Total demand; Demands by users and energy services	Total demand	Total demand	Total demand; Demands by users and energy services
-- Power generation	Decentralised generation	Large-scale generation; Decentralised generation	Large-scale generation; Decentralised generation	Large-scale generation; Decentralised generation	Large-scale generation	Large-scale generation; Decentralised generation	Large-scale generation; Decentralised generation	Large-scale generation; Decentralised generation
-- Dispatch, demand response and storage		Dispatch; Demand response; Storage, incl. hydrogen	Dispatch (stylised)		Dispatch (stylised); Demand response		Dispatch; Storage	Dispatch; Demand response; Storage
-- Transmission and distribution						Transmission and distribution	Transmission and distribution	Transmission and distribution
-- Inter-connectors to Europe		Import; Export	Import	Import		Import	Import; Export	Import; Export; UK embedding in the European

Model	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
								system
-- Non-electric parts of the energy system	Non-electric heating	Non-electric heating; Non-electric transport			Non-electric heating; Non-electric transport; Non-electric industrial and commercial uses		Non-electric heating	
Method for constructing alternative pathways (scenarios)	Modifying the assumptions according to the storylines	Modifying the assumptions according to the storylines; Merit order of power generation	Cost-optimisation and evaluation of maximally different near-optimal pathways	Input from other models	Dynamic simulation	Input from other models	Cost-optimisation	Cost-optimisation
Economic considerations			Cost-optimisation; Exploration of near-optimal pathways	Post hoc assessment	Dynamic simulation, given the heterogeneous sensitivity of the different actors to costs		Cost-optimisation	Cost-optimisation
Environmental considerations		Post hoc assessment; Operational emissions (from primary energy use); Only CO ₂ emissions	Emission constraint; Operational emissions; Only CO ₂ emissions	Input from other models	Post hoc assessment; Operational emissions; Only CO ₂ emissions	Post hoc assessment; 'Whole system' emissions (upstream and operational); Greenhouse gas emissions (CO _{2eq}); Human toxicity; Particulate matter; Agricultural land occupation	Post hoc assessment; Operational emissions; Only CO ₂ emissions	Emission constraint; Operational emissions; Only CO ₂ emissions

Model	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
Treatment of uncertainty			Structural uncertainty around cost-optimisation; Parametric uncertainty accommodated to some extent through maximally different, near-optimal pathways	Parametric uncertainty considered through ranges for uncertain parameters	Parametric uncertainty considered through probabilistic modelling			Parametric uncertainty considered through sensitivity analysis
Treatment of behaviour and heterogeneity of actors			Considered to some extent through deviations from cost-optimal pathway		Detailed modelling			
<i>Key field of expertise</i>	<i>Demand</i>	<i>Dispatch, demand response and storage; Generation</i>	<i>Maximally different alternatives; Uncertainty</i>	<i>Economic appraisal</i>	<i>Uncertainty; Behaviour and heterogeneity of the actors</i>	<i>Energy and environmental appraisal</i>	<i>Transmission and distribution; Generation; Spatial disaggregation</i>	<i>Dispatch and demand response; Generation; Transmission and distribution; Interconnectors</i>

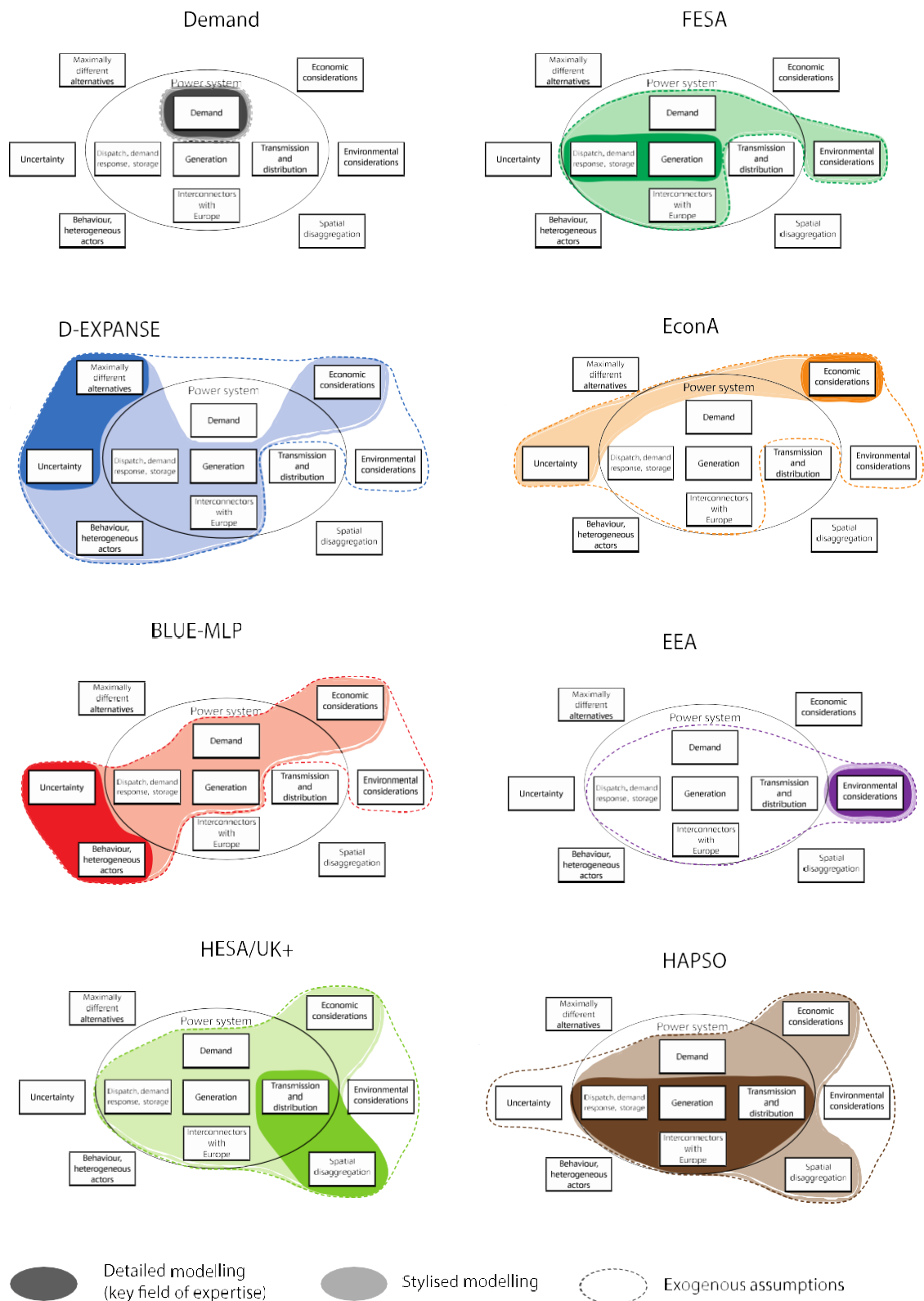


Figure 3. The landscape of models (model versions as of April 2013)

3. The process of linking the storyline with the multiple models

This Section describes the process (Figure 4) of linking the *Central Co-ordination* storyline with the insights from the eight models. First, the qualitative storyline is ‘translated’ into a set of harmonised assumptions that are necessary for conducting the model runs, specifically tailored for this storyline (Section 3.1). The models are then run with these harmonised assumptions. Second, the outputs from the models are used for revisiting the qualitative statements of the storyline (Section 3.2). Generally, neither the storyline nor the multiple models are fixed; they are all being updated given the new developments in the real world, new data sources, feedback from peer review and so on. Thus, in line with [2], the process from Figure 4 is repeated iteratively for updating the storyline.

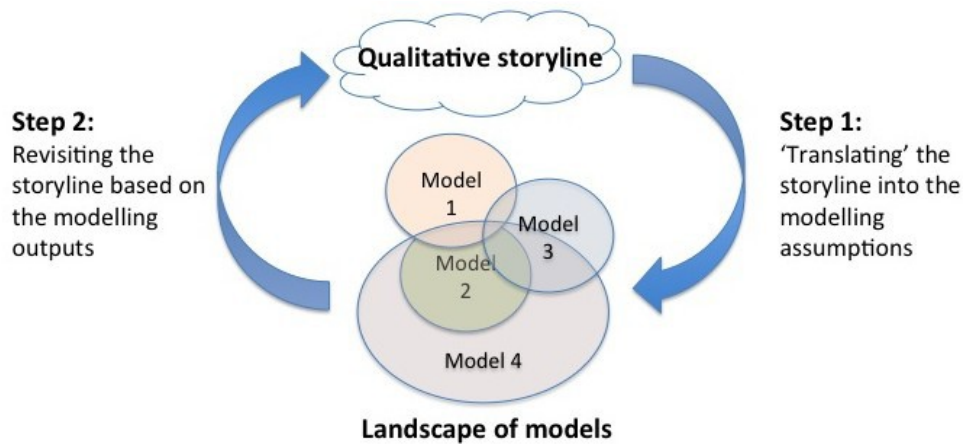


Figure 4. The iterative process of linking storylines with multiple quantitative models

3.1. Step 1: 'Translating' the storyline into the modelling assumptions

‘Translating’ such a detailed storyline *Central Co-ordination* [37, 38] into a set of harmonised assumptions that will be used by the models is a challenging task. On the one hand, these harmonised assumptions will already be a narrower representation of this qualitative storyline that is rich in detail. This is reasonable as quantitative models always represent only a part of the bigger, qualitative picture [10]. On the other hand, these quantitative assumptions should not be too narrow and should allow enough flexibility for the quantitative models to express their perspective and to make their distinct contributions. Every model has a broad range of other, model-specific assumptions. As the multiple models used for this analysis are very diverse, it is desirable to harmonise the list of the assumptions so that they could be implemented in all of the models. As a result, there are a lot of possible variations and a certain share of subjectivity involved in the process how a storyline is ‘translated’ into the model assumptions.

For translating the *Central Co-ordination* storyline into the harmonised modelling assumptions, several key aspects of this storyline are taken. These aspects are: (i) a mild growth of the power demand due to the incentives for end- use energy efficiency, (ii) the increased use of large-scale low-carbon technologies, especially of those where UK industry could take a global lead, and a medium uptake of decentralised generation, (iii) the achievement of the emission mitigation goals and (iv) low risk of investment due to the tenders for tranches, issued by the Strategic Energy Agency. More specifically, the models are tuned to match these harmonised assumptions as closely as possible:

- i. Total power demand in the UK:
 - In 2020, the total power demand, including losses, stabilises at 350 TWh/year;
 - In 2030, it increases to 390 TWh/year due to increased electric heating and electric vehicles;
 - In 2050, it is equal to 410 TWh/year.
- ii. Power generation mix in the UK:
 - In 2020, 40% of the produced power comes from low-carbon sources, prioritising coal CCS, nuclear and renewable sources. At least 25% of the produced power comes from renewable sources, such as offshore and onshore wind, wave, tidal barrage and tidal stream.
 - In 2030, the power generation mix bridges the mixes of 2020 and 2050.
 - In 2050, 75% of total produced power comes from large-scale low- carbon sources, such as nuclear, coal and gas CCS, offshore wind, wave, tidal barrage and tidal stream. At least, 25% comes from low-carbon decentralised sources, such as onshore wind and biomass combined heat and power (CHP) plants.
- iii. Greenhouse gas emissions:
 - In 2020, the average carbon intensity in the whole UK power system is 300 gCO₂/kWh of power produced;
 - In 2030, this value drops to 30 gCO₂/kWh;
 - In 2050, it is as low as 20 gCO₂/kWh.
- iv. Investment:
 - Social discount rate of 3.5% is used for the calculation.

Not all of the eight models can implement all of these harmonised assumptions. First, the Demand, FESA models and EEA cannot consider the last assumption about the discount rate as they do not consider costs at all. They, therefore, by-passed this

assumption, but implemented the remaining assumptions. Second, the EconA and EEA are appraisal techniques and require inputs about the whole power demand structure and generation mix rather than modelling assumptions. Thus, the EconA and EEA are conducted on the basis of the initial quantitative representation of the storyline (Figure 2), which is in line with the harmonised assumptions described above.

3.2. Step 2: Revisiting the storyline based on the modelling outputs

The qualitative statements from the *Central Co-ordination* storyline are scrutinised from the perspective of the outputs of every model. The storyline pictures the governance arrangements and the role of the different actors and these can hardly be interrogated by the models. But the description of the outputs of these different governance arrangements and the actors' decisions is analysed. For example, the statement "In the financial budget statement in April 2009, the UK Government formally adopts carbon budgets for the periods 2008- 12, 2013-17 and 2018-22 based on a 34% reduction in greenhouse gas (GHG) emissions by 2020 from 1990 levels" [38, p. 1] is not analysed as it describes the intention of the government. But, the statement "This is realised by the achievement of 25% of electricity to be generated from renewables by 2020" [38,p. 3] is interrogated by the eight models. The landscape of models (Figure 4) plays an important role here as it helps to highlight the key fields of expertise of every model. In this way, it becomes possible to prioritise the models in scrutinising the specific aspects of the storyline, such as the demand, generation, economic appraisal and so on.

4. Results and discussion

4.1. Revisiting the Central Co-ordination storyline

Table 2 presents the summarized results of revisiting the *Central Co-ordination* storyline from the perspective of the eight RTP models; detailed results are available in the Electronic Supplementary Material. Every qualitative statement about the outcomes of the governance and actor choices, specified in the storyline, is compared and contrasted with the modelling results.

From the perspective of these eight models, the *Central Co-ordination* storyline is fairly robust (as there are few red cells in Table 2). It can be seen that the storyline is almost completely supported by the Demand, FESA and HESA/UK+ models. This is no surprise because these three models specialise in technical feasibility assessment of the power system transitions. These models can be tailored to mimic the storyline and identify only the key mistakes of technical feasibility. Moreover, the researchers, who work with these models, played an active role in the Technical Elaboration Working Group in the original Transition Pathways project. Thus, the storyline is already partly informed by these models and it is not surprising that there is no divergence. The majority of the diverging insights come from the BLUE-MLP, HAPSO and D-EXPANSE models. These models include a broader range of considerations than technical feasibility (Table 1): heterogeneous behaviour of the key actors, uncertainty, detailed dispatch modelling and maximally different alternatives. Thus, naturally these models question the *Central Co-ordination* storyline more.

Although the results from the eight models are in line with most statements of the *Central Co-ordination* storyline, several clusters of diverging insights are identified. First, the storyline described only a mild increase in the total power demand (20% higher in 2050 as compared to 2008) due to energy saving behaviour and efficiency improvements. However, the BLUE-MLP model shows that, when the heterogeneity of the behaviour of the different actors is considered, maintaining slow power demand growth through the entire model horizon appears rather wishful thinking. Storylines developed by the various stakeholders and experts often tend to be overly optimistic and fragile from the modelling perspective [10, 11]. This remark is also consistent with a broader argument that failures of effectively mitigating climate change can be expected [64]. The *Central Co-ordination* storyline envisions a passive role of the civic society. Without the voluntary energy saving action of the civil society, drastic demand reduction may be challenging to achieve. The UK government could enforce some types of measures for mitigating the power demand, such as smart meters, efficient domestic appliances or refurbishment of buildings. But in a democratic society, a rapid and massive implementation of such measures may be problematic. Thus, the

expectation from the storyline about the demand needs to be revisited.

The *Central Co-ordination* storyline aspired to the retirement of existing coal and gas power plants by 2037 and their replacement with low-carbon technologies, such as renewable energy sources or gas and coal with CCS. However, both the D-EXPANSE, BLUE-MLP and HAPSO models, which also model the demand response potential, show that this aspiration is challenged by the dispatch (supply-demand balancing) constraint. According to the models, for the aspired high deployment of renewable energy sources there will be a need for significant levels of back-up capacity, mostly gas OCGT power plants. D-EXPANSE model, which explores the maximally different pathways, shows that at least 15 GW of gas power plants would be required. The power generation mixes of BLUE-MLP also include 15 GW of gas or coal power plants. The HAPSO model, which evaluates the cost-optimal pathway while taking into account energy security requirements, proposes 50GW of gas OCGT. The value is higher than the one suggested by the D-EXPANSE and BLUE-MLP models because the HAPSO model assumes higher supply security requirements. Overall, the complete retirement of fossil fuel based power plants is questionable and the results suggest that the storyline needs to include more of that type of plant. As highlighted in Figure 2, the dispatch modelling is the key field of expertise of the HAPSO model. Thus, its conclusion about the 50GW of gas OCGT by 2037 shall be prioritized over the D-EXPANSE and the BLUE-MLP conclusions.

The FESA, BLUE-MLP, EEA, HESA/UK+ and HAPSO models all agree that the target of the greenhouse gas emissions in 2035 would not be met. Instead of the aspired 30 gCO₂/kWh in the storyline, the modelling outcome range from 33 gCO₂/kWh to 54 gCO₂/kWh for CO₂ for operational emissions and equals to 120 gCO_{2eq}/kWh for the 'whole system' (cradle to gate) emissions. The D-EXPANSE model shows a number of power generation mixes that could meet the target of 30 gCO₂/kWh, but these mixes are different from the mixes evaluated by the other models. Thus, while reaching the emission target can be technically feasible, this may not be realistic via the means that the storyline describes. According to the EEA, if the 'whole system' emissions were considered, then the target would also be missed (although a different target for the 'whole system' emissions could be expected). Thus, either the achieved levels of emissions or the measures (power demand and generation mix) need to be revisited in the storyline.

When the *Central Co-ordination* storyline was initially developed in the Transition Pathways project, it had little insights from the experts and models, informed by the economic considerations [37]. This is reflected in the points of divergence between the models and the storyline about the power generation mix. The

D-EXPANSE, BLUE-MLP and HAPSO models, which include information about costs, the cost-optimal and near-optimal decisions of actors, both include more nuclear power than anticipated by the storyline. The D-EXPANSE model prioritises onshore and offshore wind power as renewable energy sources rather than wave and tidal power, as envisioned in the storyline. The BLUE-MLP model includes a much more significant deployment of nuclear power due to its costs and emissions performance. The HAPSO model raises concerns about significant curtailment of the power produced by the renewable energy sources due lack of market integration and subsequent development of interconnectors between the UK and the continental Europe. This significant curtailment would reduce the economic feasibility of these sources. While the storyline also describes a high deployment of gas and coal CCS, the D-EXPANSE model shows that many of the cost-optimal and near-optimal pathways could have no CCS in the generation mix. The HAPSO model also questions the large deployment of CCS because, from the dispatch perspective, these plants would run on a low capacity factor (24% to 36%) and thus their economic feasibility is challenged. In brief, these results suggest that a revised version of the *Central Co-ordination* storyline should consider a higher share of nuclear and wind power, but a more pessimistic deployment of coal and gas CCS and other types of renewable energy sources.

The *Central Co-ordination* storyline identifies the technical and economic feasibility of CCS as one of the key risks for implementing the storyline. While most of the eight models include a share of coal and gas CCS, the D-EXPANSE model shows that this is not a prerequisite. D-EXPANSE generates a large number of maximally different cost-optimal and near-optimal scenarios (30% deviation from the least cost scenario). Many of these scenarios do not have CCS. This means that the coal and gas CCS are not prerequisites for implementing the *Central Co-ordination* storyline, as it is described in the harmonised assumptions. As coal and gas CCS is a relatively costly technology, it appears seldom in the cost-optimal and near-optimal scenarios. In the D-EXPANSE modelling outputs, the environmental gains of the coal and gas CCS are rather replaced by the deployment of other low-carbon technologies (renewable sources and nuclear power), while the role of back-up capacity of coals and gas CCS power plants is compensated by coal and gas plants without CCS. The BLUE-MLP model also provides a range of power generation mixes without CCS. Thus, instead of suggesting the feasibility of CCS as the key risk, these results seem to imply that *Central Co-ordination* storyline shall consider other risks that are highlighted by diverging insights from the eight models. One of these key risks is the supply- demand balancing challenge. As the HAPSO, D-EXPANSE and BLUE-MLP models show, supply-demand balancing may be a big challenge in the *Central Co- ordination* storyline and this may cause public concerns

over supply security. Another key risk is the failure to meet the greenhouse gas emissions target. The results of these multiple models from Table 1 already show that the target might be missed in 2035. This failure would become even more likely if, in order to meet the balancing challenge, the needed gas power plants would be installed as the back-up capacity. The third key risk is the need for nuclear power, which—as the recent years show—may cause a high public resistance.

Despite the fact that the *Central Co-ordination* storyline is very detailed, it seems to miss or under-represent several aspects that are analysed in the eight models (Figure 3). The storyline does not describe any arrangements regarding power import and export as well as the relations with the other European countries, as modelled by the HAPSO and D-EXPANSE models. The storyline does not discuss the governance arrangements and the choices of actors about the power transmission and distribution grid, covered by the HESA/UK+ and HAPSO models. The demand response levels, important for the dispatch modelling by the FESA, HAPSO and other models, have also been only described to a limited extent. The D-EXPANSE and BLUE-MLP models analyse the influence of parametric and structural uncertainty on the power system transition, but these insights are so far not incorporated into the storyline. The above-listed aspects could be considered, when developing the next version of the storyline.

4.2. Discussion on the generalised process

In the Section 4.1 the limitations of the *Central Co-ordination* storyline were identified from the perspective of eight models (Figure 3). This Section 4.2 critically reflects the reported process of linking the storyline with the multiple models in the RTP project and highlights procedural insights, relevant for the general approach (Figure 2).

Table 2. Revisiting the storyline with the multiple models (detailed documentation is available in the Electronic Supplementary Material). **Green** colour means that the model outputs are in line with the storyline, **yellow** – that there is a minor divergence, **red** – that the storyline statement contradicts the model outputs, **white** – the particular statement is not addressed in the model.

Some of the relevant quotes from the storyline, taken from [38]. The complete list of quotes is available in the Electronic Supplementary Material	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
2008 -2022								
"By 2020, the energy efficiency measures have led to the stabilisation of electricity demand."								
"This policy involves a risk being passed to consumers of experiencing higher than average electricity costs, if the price of natural gas does not rise significantly."								
"By 2020, <...> the relative decarbonisation of electricity supply has led to the achievement of the carbon budget of a 34% reduction in CO ₂ emissions, compared to 1990 levels."								
"This is realised by the achievement of 25% of electricity to be generated from renewables by 2020."								
"High levels of deployment for onshore (8GW) and offshore wind, (10GW) which operates at over 40% capacity factor; the first operational CCS coal plant; and four new (1.6 GW) nuclear power stations."								
2023 -2037								
"Remaining other coal and gas power stations are retired as they reach the end of their life."								
"This leads to the further penetration of onshore and offshore wind (though at a lower rate of deployment than in earlier periods) and scaling up of wave and tidal power schemes, as a result of experience gained through earlier demonstration projects."								
"The commercial viability of CCS increases, thanks to earlier investment in demonstration projects and a high carbon price."								
"A total of 12 new (1.7 GW) nuclear power stations being in operation by 2030"								
"Energy service demand reduces, thanks to household and industrial energy efficiency measures"								
"The [electric vehicle] fleets are coordinated to allow a proportion of them at any time to act as system regulators, to facilitate the penetration of high levels of inflexible generation. This system is having a major positive impact on grid management by distribution network operators by the 2030s."								

"Domestic electricity demand rises due to the adoption of electric heating for 60% of domestic heating systems"								
"Overall, electricity demand only rises by just over 10% from 2020 to 2035"								
[From 2020 to 2035] "The carbon intensity of electricity generation improves significantly to less than 30 gCO ₂ /kWh (though higher when calculated on a life-cycle basis)"								
2038-2052								
"So, total electricity demand in 2050 is only 20% higher than in 2008."								
"The deployment of both domestic and non-domestic distributed generation increases, meeting around a quarter of total demand by 2050, with significant shares from onshore wind and biomass CHP systems."								
"The centralised generation system is now almost totally decarbonised, with eighteen large nuclear power plants with a total of 30 GW capacity providing the largest share of generation. There is significant further investment in CCS systems, resulting in 10GW of coal with CCS and 20 GW of gas with CCS by 2050. Overall, 65 GW of renewables capacity is installed, mainly onshore and offshore wind and wave and tidal power."								
"The average carbon intensity of electricity generation has now been reduced to below 20 gCO ₂ /kWh by 2050, resulting in the almost complete decarbonisation of power generation, though carbon emissions are significantly higher when calculated on a life-cycle basis."								
Key risks								
"Carbon capture and storage turns out to be technologically or economically unfeasible"								
"Higher energy service costs resulting from high levels of low-carbon investment."								

The starting point of this analysis was the *Central Co-ordination* storyline that was developed in the original Transition Pathways project [37, 38]. This storylines is lengthy (five pages) as it aimed to richly represent the complex power system transition. The storyline also aimed to encapsulate numerous details, coming from the different parts of the power system, viewpoints (government, power companies, consumers etc.), stakeholder and expert inputs. Such a process, however, has shortcomings. First, when so many diverse inputs are brought into one storyline, the internal consistency of this storyline becomes at risk. The comparison of the storyline with the outputs of the eight models revealed several inconsistencies. For example, the storyline describes the role of civil society as passive, while the envisioned substantial decrease in the energy service demand may not be feasible without voluntary action of energy consumers. In order to avoid such cases, it seems likely that the development of internally consistent, stakeholder-based storylines, facilitated by formal techniques such as cross-impact balance or formative scenario analysis [5, 12, 19-21], would increase the robustness of the qualitative storyline itself.

Second, some of such internal inconsistencies as well as other mistakes due to the lack of analytical foundation can be eliminated by comparing the storyline with the models (given that these models are available), as done in this paper. This is essential because the power system transition is inherently complex and qualitative storylines-based approach on its own cannot capture this complexity [11]. The afore-mentioned cross-impact balance or formative scenario analysis can be used for mediating among the diverging perspectives of the experts. The insights from the multiple models could thus perhaps be brought into these analyses too in order to derive storylines that are informed by multiple models and multiple stakeholder views simultaneously.

Third, lengthy and detailed storylines may be easier for the audience to imagine, but they also lead to overconfidence about how realistic they are [12]. This is problematic because such exercises distract the attention of the audience from other, as likely or as desirable, scenarios. The scenario approach is expected, however, to expand rather than narrow down the understanding about the plausible futures. Therefore, there is a threshold for how long and detailed the storyline shall be. When storylines are combined with the multiple models as in this paper, a meaningful approach would be to keep in the storyline the details about the governance and the choices of the actors, while leave the power system description to the multiple models.

The way a qualitative storyline is 'translated' into the assumptions for the quantitative models (Step 1 in Figure 2) is decisive for the comparison of the storyline and the modelling results. There is a trade-off between the number of assumptions and how much flexibility the models have to express their perspective. If a large number of

assumptions is used, the models would be tailored to mimic the storyline almost completely. In this way, the added value of models, which have different rationales than described in the storyline, would be ignored. For example, the cost-optimising models, like HAPSO or D-EXPANSE, could be tailored to produce the results, similar to the storyline if there are no major inconsistencies in the storyline. But this would gloss over the fact that the cost-optimal and near-optimal—thus, perhaps more realistic pathways—may be very different than the one described in the storyline. The modelling assumptions thus shall better allow more flexibility for the models to express their perspective. However, it is challenging to define what the optimal number and type of assumptions are. Moreover, one qualitative statement might have a range of quantitative representations which need to be captured systematically [10, 11]. The ‘translation’ procedure, used in this paper, is acknowledged as one of the weaknesses. To some extent, this fragility arose because only one storyline was analysed through the perspective of the eight models. If all three storylines of the RTP project were analysed (*Central Co-ordination*, *Market Rules* and *Thousand Flowers*), this problem could be resolved to some extent, as a unified framework for the ‘translation’ of these storylines into modelling assumptions would need to be defined. By comparing three storylines, a more robust framework could be developed.

The landscape of models (Table 2 and Figure 3) proved to be a useful approach for understanding and mapping the fields of expertise of the eight, very diverse models of the RTP project. This landscape helped to understand where the models overlap and where they have their key, individual fields of expertise as compared to the other seven models. In line with [16], this landscape approach assumes that the usefulness of the model is the local matter. There is no single best model that covers all the relevant aspects in sufficient depth and breadth. The usefulness of the model depends on the model’s suitability to answer the specific question at hand and to fill a gap among the other existing models. In the reported process, due to their different key fields of expertise, all eight models proved to be useful for assessing the storyline (Table 2). However, this landscape of models is not complete because not all of the qualitative statements in the storyline could be assessed. First, the statements about wider developments of industry and the national economy could not be addressed. For this purpose, a macro-economic model or a whole energy system model would be needed in the landscape. This whole energy system model would need to be broader than the already used HAPSO model, which addresses only the power system. This model would need to have as wide system boundaries as UK MARKAL or TIMES [45, 65] and to address the whole supply chain of the whole energy system (not only the power system) and energy-economy interactions.

Second, assuming a substantial deployment of distributed generation, there would be a need for improved modelling of local voltage control and two-way power flows. This problem would increase even more if the *Thousand Flowers* storyline would be analysed, because this storyline pictures a significant uptake of decentralised generation. A model that addresses these issues would need to be added to the landscape of models too.

Third, the storyline raised issues about public acceptability of rising energy prices or, as suggested by the models, possibly decreasing supply security due to the deployment of intermittent renewable energy sources. While the public acceptability issues are challenging to model, they are of high relevance for the future transitions. Therefore, in parallel to the modelling-based assessment of the storyline, a social scientific assessment is required. This social scientific analysis already took place in the Transitions Pathways project [66] and thus, together with the landscape of models, it could improve the analytical assessment of the qualitative storylines.

The iterative loop in Figure 2 would be completely closed by revising the qualitative storyline on the basis of the results of the eight models. The exercise, reported in Table 2, helped to identify the points of fragility of the storyline. The diversity of the eight models here proved to be especially useful as the results of the different models were at times diverging. While some models were in line with all or almost all storyline statements, there was almost always at least one model that diverged from the storyline. Any of these divergences can have credible reasons leading to the fragility of the storyline. Unpicking the underlying mechanisms of this divergence (as already reported in Section 4.1.) is thus essential for understanding why this divergence appears and, if necessary, revising the storyline. The next step of this process would be a collaborative, reflexive effort between the storyline developers and the modellers. In this way, an improved storyline version could be developed.

The iterative loop in Figure 2 is a two-way reflexive collaboration between the storyline and the models. In this paper, a storyline-led approach is reported. The storyline was developed first and then was assessed from the perspective of the different models, at the same time reflecting on the potentially relevant models that were missing from the analysis. Models alone can hardly capture the broader picture, covered in the storyline, such as the power system governance 'logics' and the choices of the key actors. As these aspects are very challenging to model, it is meaningful to use a storyline-led approach. However, an alternative, modelling-led approach could also be used to derive storylines too. This could be based on the generation of a large number of scenarios with multiple models and extracting a smaller range of scenarios

with fundamentally- different structures and describing them in storylines. Some research in this direction is already reported in [6, 11, 52, 53, 67-69]. Such process could be organised similar to the process of Figure 2, but it would start with the modelling exercise.

5. Conclusions

This paper extends the current state-of-the-art approach for linking qualitative storylines with quantitative models. An approach is proposed for linking a very detailed storyline, which describes the governance 'logics' and the choices of key system actors, with multiple, very diverse quantitative models. This approach is especially relevant because a growing number of interdisciplinary projects worldwide tend to bring together social scientists with modellers. Most of these models already exist before the projects and differ substantially in their disciplinary perspective, model objective, system boundaries and the format of inputs and outputs. Cross-comparison of such models is a challenge in itself. In the proposed approach, the comparison of the models is based on the concept, called the landscape of models. Even more, this paper goes further by linking these multiple, diverse models with qualitative storyline. Therefore, the described approach is a novel contribution to the existing literature.

In the frame of the Realising Transition Pathways project, the proposed approach is illustrated by revising the *Central Co-ordination* storyline, developed in the earlier Transition Pathways project, for exploring the UK power system transition until 2050. This storyline describes the governance 'logics' and the choices of the key system actors, when the UK central government takes a more active role in shaping the power system transition. Such soft considerations as governance and the actors' choices can hardly be modelled in the current RTP models; this highlights the value of the storyline. This qualitative storyline is addressed through the perspective of six, very diverse models and two appraisal techniques: Demand, FESA, D-EXPANSE, EconA, BLUE-MLP, EEA, HESA/UK+ and the HAPSO models. These models and appraisals revealed the fragile nature of the storyline. The storyline tended to overestimate the power demand reduction potential, the uptake of marine renewables and the importance of CCS feasibility. But it underestimated the supply-demand balancing challenge, the need for gas power plants as a back-up capacity, the role of nuclear power and interconnectors with Europe, and the challenge of meeting the long-term stringent greenhouse gas emissions targets. Thus, the combination of the qualitative storyline and its revisions from the perspective of multiple, diverse models is key for developing robust future scenarios and transition pathways. An iterative process

for this purpose has been proposed in this paper.

Acknowledgements

The authors thank the other members of the Realising Transition Pathways and the preceding Transition Pathways projects, who developed the *Central Coordination* storyline and participated in the modelling workshops. The earlier contributions of Graham Ault, Stuart Galloway, Geoff Hammond, Matt Leach, Goran Strbac, Murray Thomson to the models are also acknowledged. The authors especially value the extensive critical review by Geoff Hammond and Peter Pearson that helped to considerably improve the manuscript.

Role of the funding source

This work was conducted as a part of the Realising Transition Pathways project, supported by the UK Engineering and Physical Sciences Research Council (Grant EP/K005316/1). The funding source was not involved in the study or in writing this paper.

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6.6 Key Outputs

A multidisciplinary approach was developed in this paper for linking qualitative storylines to multiple cross-scale quantitative models. An iterative process was proposed to identify areas of divergence and recommend revisions that could enhance the robustness of the scenario. In doing so, this process provides better understanding of the potential development of the UK electricity system under a government-led regime; thereby contributing to the delivery of objective 4 of this thesis.

The following inconsistencies between the storylines and the eight diverse models were identified.

- Storyline overestimates the potential for power demand reduction by government intervention alone.
- Greater backup capacity is required to satisfy supply-demand balancing.
- Interim 2035 GHG reduction targets are not met by models and life cycle GHG emissions appear significantly higher.
- There was an over reliance on Coal and gas CCS to deliver the pathway's GHG emissions reductions. The technology proved too costly at this level of deployment, and not capable of delivering such high GHG reduction on a life cycle basis.
- The storyline failed to describe arrangements regarding power import and export, and the role of European countries.
- The governance arrangements for the transmission and distribution grid were also not covered by the storyline.
- Limited information was provided by the storyline on the demand side participation response levels.

The storyline had already acknowledged the technical and economic feasibility of coal and gas CCS as a key risk to the pathway. However, insights from various models suggest that coal and gas CCS was not a prerequisite for this pathway. Additional risks were identified by the models such as meeting the supply-demand challenges, failing to adhere to GHG reduction targets, and ensuring the delivery of a number of nuclear plants in the face of public resistance.

The exercise of linking a qualitative storyline to multiple cross-scale quantitative models provided important insights which greatly enhanced the understanding of the future development of UK power sector, and highlighted key revisions to improve the robustness of the *Central Coordination* pathway.

7 Article IV – ‘Reconciling qualitative storylines and quantitative descriptions: an iterative approach’

7.1 Unpublished Manuscript

E. Robertson, Á. O’Grady, J. Barton, S. Galloway, D. Emmanuel-Yusuf, M. Leach, G. P. Hammond, M. Thomson, T. Foxon, 2016. *‘Reconciling qualitative storylines and quantitative descriptions: An iterative approach’*

Submitted for review on the 15th of April 2016

7.2 Contribution to Research

Over the course of the RTP project, extensive research was carried out to improve the elaboration of the pathways, through the application of multidisciplinary and interdisciplinary methods. This manuscript was a synthesis of this research into a formal process for the quantitative elaboration of socio-technical scenarios, drawing on the Transition Pathways approach. This work expanded on their original elaboration, and the linking of their storylines to models across the consortium, as discussed in Article III. An iterative approach was proposed to allow for the better integration of storylines and models, and thus, the development of more robust and comprehensive scenarios.

This work builds on article III, contributing to the delivery of objective 4 of this thesis, by further enhancing modelling techniques to better inform the future development of the UK electricity sector. A four stage interdisciplinary methodology was developed to transform a qualitative storyline, into consistent quantitative descriptions, which were internally consistent with one another. The resulting unified platform formed the foundation for wider interdisciplinary research. Consequently, over-arching insights can be more readily deduced across multiple disciplines, leading to more holistic findings which could better support current decision-making.

7.3 The Significance and Originality of the Article

The work proposes a new approach to scenario development which fully reconciles qualitative storylines and their quantitative representation through a structured interdisciplinary methodology. Interdisciplinary projects are on the rise in order to fully assess and address complex societal problems. It is asserted that this formal process could provide guidance to build robust future scenarios not only for socio-technical storylines but could also be used for the quantification of any qualitative storyline.

7.4 Contribution by Candidate

Second author (generating 35% of content)

From the beginning of the RTP project, the candidate has been a key contributor to the working of the *Technical Collaboration Group* (TCG), which refined and enhanced the quantitative elaboration of the pathways. The candidate co-jointly developed the concept of the paper with the lead author, and also mapped the structure of the paper based on their work within the TCG group.

The candidate drafted the methodology and related diagrams, and also contributed to introduction and discussion. A critical revision was performed by the candidate of the manuscript, addressing any knowledge gaps. A final review of the completed paper was also conducted.

Reconciling qualitative storylines and quantitative descriptions: An iterative approach

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Abstract

Energy system transition research has been experimenting with the integration of qualitative and quantitative analysis due to the increased articulation it provides. Current approaches tend to be heavily biased by qualitative or quantitative methodologies, and more often are aimed toward a single academic discipline. This paper proposes an interdisciplinary methodology for the elaboration of energy system socio-technical scenarios, applied here to the low carbon transition of the UK. An iterative approach was used to produce quantitative descriptions of the UK's energy transition out to 2050, building on qualitative storylines or narratives that had been developed through the formal application of a transition pathways approach. The combination of the qualitative and quantitative analysis in this way subsequently formed the cornerstone of wider interdisciplinary research, helping to harmonise assumptions, and facilitating 'whole systems' thinking. The methodology pulls on niche expertise of contributors to map and investigate the governance and technological landscape of a system change. Initial inconsistencies were found between energy supply and demand and addressed, the treatment of gas generation, capacity factors, total installed generating capacity, installation rates of renewables employed and the amount of electricity used by battery electric vehicles. Knowledge gaps relating to the operation of combined heat and power, sources of waste heat and future fuel sources were also investigated. By adopting the methodological approach to integrate qualitative and quantitative analysis the resulting elaboration is far more comprehensive, providing a stronger basis for wider research, and for deducing more robust insights for decision-making. It is asserted that this formal process helps build robust future scenarios not only for socio political *storylines* but also for the quantification of any qualitative storyline.

Keywords

Scenarios, storylines, energy, climate change, interdisciplinary, quantification

Highlights

- Bridging the gap between qualitative storyline and quantitative models & analysis
- Present an interdisciplinary methodology for the elaboration of socio-technical scenarios
- Interdisciplinary analysis of the low carbon transition of the UK power system to 2050
- Present quantitative descriptions of the UK electricity system scenarios to 2050
- Utilizing niche expertise to inform the landscape to increase certainty of transitions

1 Introduction

In recent years, the energy sector has undergone strong and prolonged change which is set to continue [1], giving rise to high levels of uncertainty moving forward [2]. In this setting, scenarios and storylines offer a means by which these uncertainties can be captured by exploring possible (although not necessarily equally likely) futures. Storyline approaches of this type have therefore become widely used in the energy arena as a method of adding context and solving problems [3]. Examples of scenario development and analysis can be found in the UK in academia [4-8], government [9] and from system operators [10] alongside international examples from Denmark [11] and Japan [12], together with global examples [13, 14]. The development of future energy system scenarios is highly prevalent and has become common practice in many fields in order to demonstrate system change through modeling and analysis [3].

In the UK the DECC 2050 pathways were designed by the Department of Energy and Climate Change (DECC) to try and answer questions with regard to demand, electricity production, fuel sourcing, technology choices and decarbonisation of the energy supply out to the year 2050 [9]. The analysis, that accompanied the release of the DECC 2050 calculator [9, 15], presented six *illustrative* pathways to demonstrate the variety and wide range of possible futures that could be explored, with no preference stated or panacea promoted. These pathways, draw on previous work [16, 17], which examined six future electricity network scenarios for Great Britain in 2050, concluding that the main influences of scenario development will be from highly uncertain economic, political and technological factors.

Scenarios may be classified in many ways and one prevalent divide is between quantitative scenarios and qualitative storylines [16]. Both approaches bring their respective advantages when carrying out future-oriented research. Qualitative storylines provide a wider view of a transition, capturing features such as governance and behavioural change. Quantitative scenarios provide technical depth, describing the transition with empirical real-world data. However, qualitative storylines lack technical robustness and can often be fraught with bias from its development. In contrast, quantitative models have a more narrow focus, and only represent specific elements of the system under transition. Consequently, research groups are starting to combine the approaches, and experimenting with their integration to benefit from the richness that this supplies. A critical survey of energy scenarios to 2050 saw “little evidence of such combined approaches” [19] in the literature but did argue there are “strong arguments for paying increased attention to governance and legitimacy issues in the identification of policy-relevant scenarios for quantitative modelling”.

Such a combined approach was developed by the Realising Transition Pathways (RTP) consortium when assessing the UK’s transition to a low carbon economy [18]. This interdisciplinary research grouping comprised nine UK academic institutional partners, bringing together power systems engineers, environmental scientists, social scientists, energy economists and socio-technical transition scholars. The research within the RTP consortium centres on the analysis and examination of three transition pathway storylines developed by the first phase of the project, the ‘Transition Pathways to a low carbon economy’ (TP) consortium. These transition pathway storylines describe plausible evolutions of the UK towards a low carbon economy to 2050 [19].

The three RTP pathways are differentiated by their dominant governance logics. The first entitled ‘Market Rules’ is based on a ‘business as usual’ approach of large vertically integrated

firms continuing to supply the majority of the energy to the UK through the use of large-scale centralized plant. Early and firm action is taken by the government in pathway 'Central Co-ordination' with the government stepping in to ensure that targets are met by using a mixture of large scale wind, nuclear and carbon capture and storage (CCS) coal and gas plants. In the pathway 'Thousand Flowers' however there is much greater community engagement with the low carbon agenda and a strong push from the beginning to allow diverse local solutions to fill demand rather than the current dominance of large scale energy companies.

Transition pathways (classified as socio-technical *storylines*), as described in [20] and [21], are derived from an engineering and social examination of the key actors associated with "the co-evolution of technologies, institutions, business strategies and, also, user practices" and can be defined as highly qualitative in nature. For the purpose of numerical and empirical examination it was necessary that these qualitative *storylines* were quantified. Quantification was undertaken by an interdisciplinary team working to create numerical descriptors as well as expand and develop the transition pathway *storylines*. This paper presents an iterative approach to the quantification of the pathways, which takes account of the socio-political drivers for the pathways to develop quantitative descriptions that are coherent and consistent with the qualitative *storylines*.

Quantitative storylines are those identified as having little or no qualitative drivers or descriptors [22] and although technically rigorous, they typically lack the inclusion of social actors, thus weakening the robustness of insights [23]. The method proposed herein for the quantification of qualitative storylines increases robustness of findings by adding depth of knowledge to a greater breadth of understanding, and by placing the work in an interdisciplinary context. Drawing on expertise and insights from many disciplines adds greater credibility to analysis, with contributions from multiple fields of study. Consequently, better insights could be drawn and smaller nuances be recognised and then investigated.

Trutnevyte et al. [24] discusses the landscape of models within the Realising Transition Pathways consortium and the process of linking those models to transition pathway storylines in an effort to improve them both. The work of this paper builds on this effort and presents a formal approach to storyline quantification: the iterative approach, to 'bridge' this gap further and provide an approach that can be applied by others. This methodology works to create a technologically feasible quantification of a qualitative storyline whilst staying true to its central philosophy. Trutnevyte et al. [24] identified that the process and product of scenario analysis are equally important. Energy transitions are very complex and through the interdisciplinary quantification of a storyline there is a transfer of knowledge. Thus individual as well as collective pieces of work are improved and understanding is increased. Using the iterative approach proposed herein, the final output of storyline quantification is a far superior and more technically robust elaboration of the pathways than in previous attempts within the RTP consortia. It is asserted that this formal process helps build robust future scenarios not only for socio political *storylines* but also for the quantification of any qualitative storyline.

The remainder of this paper will begin in section 2 by introducing then describing a methodology for the quantification of qualitative storylines. Section 3 then details the results of the application of the methodology to the *transition pathway* qualitative storylines over two iterations including results from an investigation stage. Section 4 discusses the results detailing the improvements the iterative approach facilitated and finally section 5 concludes.

2 Methodology

2.1 Introduction

A four stage interdisciplinary methodology was developed by the RTP consortium for the quantitative elaboration of the transition pathways storylines. This methodology expands on previous work carried out in the consortium [25], providing a formal process for the quantitative component of the complete (both qualitative and quantitative) elaboration of social-technical scenarios. This framework was employed to increase the consistency between qualitative storylines and quantitative models. The resulting unified platform resulting from this process, allowed insights to be deduced more readily across multiple disciplines, leading to more robust findings which better support current decision-making. The quantitative elaboration of the storylines was mostly carried out by and coordinated by a dedicated team within the Transition Pathways consortium, known as the Technical Elaboration Working Group (TEWG). In phase 2 of the project, Realising Transition Pathways, this role was continued by a similar team known as the Technical Collaboration Group (TCG).

A generic version of the iterative methodology can be seen in Figure 1. The 4 stages of the methodology as shown in Figure 1 are applied by the TP and RTP consortia in a less generalized version as seen in Figure 2 with verification and investigation methodologies specific to the consortia and their objectives. In generality though this 4 stage methodology could be applied structurally in the same way to a variety of projects that start from a qualitative storyline and want to develop qualitative descriptions. For the TP and RTP consortia the verification process must be selected to properly address the particular problem(s) under consideration along with appropriate choices for the investigation stage. Through the application of this iterative process significant added value can be brought.

With reference to the TP/RTP specific methodology as seen in Figure 2 the three transition pathways storylines previously developed by the consortium [26] provided the preliminary basis of this process. The first stage of the methodology, 'Initialisation' generated the initial demand and supply side quantifications of the storylines. This led to stage two, the 'Unification' of the demand side and supply side quantifications. Establishing that generation met demand projections across the time projections and was completed during stage three, 'Verification', using the Future Energy Scenario Assessment (FESA) tool [25]. These first three stages of the methodology were carried out independently of each of the three transition pathway narratives, but in parallel to one another, to give more flexibility to their distinct elaboration. At each stage of the process, the elaboration of the Market Rules pathway naturally tended to precede the other two pathways and was used to develop the evolving methodology alongside the verification tools and techniques. Finally, outputs were tested using various methods in the fourth and final stage of 'Investigation'. This final stage was critical not only to establish better links between the storylines and the multiple models and assessment tools employed [24], but also to assess the plausibility of the quantifications more comprehensively [27], and to identify areas which required further consideration.

Quantification of socio-technical storylines: Iterative Approach (Generic)

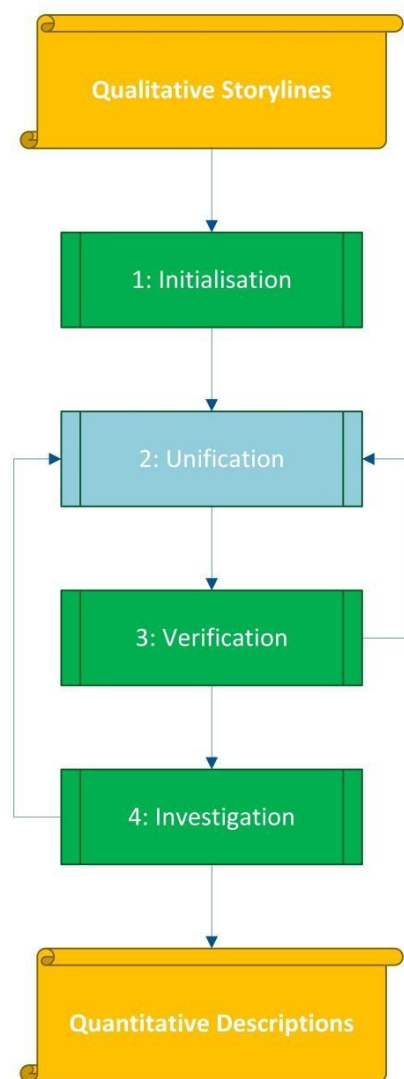


Figure 1 Generic methodology framework: bridging storylines to quantitative descriptions.

2.2 Stage 1: Initialisation

The three core Transitions pathways storylines, which form the qualitative elaboration of the pathways, were used as the basis for the development of their quantitative descriptions. The storylines were developed based on a critical review of international scenarios, stakeholder workshops with policy experts, businesses and NGOs, and interviews with critical energy system ‘gatekeepers’[28]. A more detailed account of their development can be found here [19, 29]. An interdisciplinary team from across the TP and RTP consortia evaluated these pathways, adding richness by drawing on their own particular expertise, whilst remaining faithful to the respective pathway’s logic. These pathways were explored using a range of modelling and assessment tools, which required input assumptions and further elaboration from the storyline. Depending on the individual researcher’s focus and expertise, similar assumptions may diverge, in particular when not explicitly covered by the storyline [24].

The initial quantification of these social-technical storylines began by extracting specified numbers, or indicative phrases such as “high rate of deployment” from the actual storylines [29]. Particular attention was given to dates of importance indicated across the timeline out to 2050. Researchers then extrapolated these particulars in accordance to their own field, increasing richness relating to their specific knowledge area. Undertaking this analysis with an interdisciplinary team strengthened the pathways, adding confidence and depth to the wide scope covered. Traditionally, demand side modelling is carried out first, followed by supply side, however this project deviated slightly from this approach in an effort to interrogate the interplay of the two sides [30]. A bottom-up, sectorial approach was taken in the demand quantification giving particular attention to residential energy use and private passenger transport. For industry, services sector and other transport’s electricity, their use was projected based on results from the existing modelling by the UK Department of Energy and Climate Change (DECC), tailored to match the trends in the pathway’s storylines. A more detailed account of the demand side modelling is available here [30].

The supply side quantification was first shaped by drawing on data from the Digest of UK Energy Statistics [31] and data from the National Grid’s Seven Year Statement [32]. This data was used to determine near term certainties, and offer guidance on long-term trends. The generation mix for each transition pathway storyline was then developed, primarily based on the storyline, in the view to deliver sufficient generation capacity to meet demand. A further account of the supply side modelling can be found here [25]. The output of this initialisation stage was an initial quantification of the supply and demand of the GB energy system in five year intervals for all three transition pathways.

2.3 Stage 2: Unification

The initial quantifications of demand and supply for the pathways were developed in parallel and not together, drawing on different input expertise. After the initialisation stage, it was necessary to unify both sides of the energy system represented. This was not only to ensure consistent interpretation of the storylines but also to ensure uniformity of final annual power produced and consumed. Unifying supply and demand was a highly iterative process which benefited greatly from an interdisciplinary approach. Not only did interdisciplinarity ensure a more robust representation of the storylines across supply and demand but it also circumvented a more conservative traditional approach, entrenched in today’s thinking [33].

As a result, a more realistic, uniform and robust quantification of the pathways was developed,

from a wider knowledge base. The three technical quantifications of the pathways were produced for the UK energy system out to 2050 which were not just evolutionary, but revolutionary in some cases also. Large systemic changes are seen in all three pathways, particularly in Thousand Flowers which sees a move to a highly distributed system. This technical elaboration of the storylines benefited from the historical analysis of the dynamics of transitions. This analysis provided insights into past branching points which explored large systemic transformations which occurred in a comparatively short timeframe [34]. It also drew on an assessment of the role of actors and institutions in energy system transitions using an action space approach [29]. The unification of demand and supply, was a flexible process to permit the integration of findings from research across the TP and RTP consortia's multidisciplinary and interdisciplinary analysis, and also data from further afield including sources such as [35-39]. Nonetheless it was always ensured throughout the process that the quantitative descriptors remained in keeping with the original logic of the respective pathways.

2.4 Stage 3: Verification

The initialisation and unification stages depicted overall demand and supply statistics for the GB power system to 2050. Although the system balanced in terms of units of electricity generated/consumed annually, with no explicit dispatch, the generation mix on an hourly basis remained unknown. Accordingly, each pathway was assessed in turn using the FESA model to establish their technical plausibility, functionality over different temporal load profiles, and if system balancing was possible. FESA is a single year UK power supply and demand model, incorporating hourly dispatch using real, concurrent weather data from across the UK to calculate renewable potential [25, 30]. Met Office weather data from 2001 for temperature, wind speeds, wave height and solar radiation was paired with energy demand data to predict the output of onshore and offshore wind, wave power, photovoltaics and solar water heating systems, in conjunction with predicting the operation of Combined Heat and Power (CHP) and electrical heating. Electricity supply from uncontrolled (such as variable renewables) and inflexible generation were subtracted from demand on an hourly basis to establish the net demand which must be met by dispatchable generation. As a result, FESA not only models the peaks and troughs of demand but highlights system balancing issues that must be overcome. Therefore, FESA was able to inform necessary changes to generation capacity and capacity factors to achieve system balancing. Furthermore, FESA revealed the potential for Demand Side Participation (DSP) implementation [30]. It can predict the level of time shifting of 'smart loads' that can be employed to make use of surplus electricity and also level out demand.

FESA's findings were fed back into the supply quantification of the pathways through the feedback loop seen in Figure 2. As the flexibility provided by DSP was already contained in the demand side quantification only the supply side quantification required adjustment to ensure system balancing. Similar to the matching carried out in section 2.3, system balancing was a highly iterative process benefiting significantly from an interdisciplinary approach. Each change implemented to the GB supply was validated by the TEWG/TCG for robustness in order to ensure that these new updates were probable and in keeping with a pathway's ethos. The final output of this verification stage was the first version of the technical elaboration of the transition pathways. These formed the quantitative descriptions of the pathways which provided a consistent basis for wider modelling and analysis carried out across the TP and RTP consortia.

2.5 Stage 4: Investigation

Both the qualitative storylines and quantitative descriptions of the pathways provided a coherent foundation for the modelling and research across the TP and RTP consortia. Outputs from multiple analyses were then more readily comparable and could be combined to deduce crisper cross-cutting findings to help tackle energy and climate change issues. The quantification of the transition pathway storylines formed the input assumptions for empirical quantitative modelling and qualitative analysis, whilst the storylines provide a wider political, social and cultural context.

Using the qualitative storylines and quantitative descriptions as a consistent platform for all modelling and analysis, across various fields, insights derived from this research can also be used to test the pathways and feedback into another iteration of the quantification of the pathways. Various modelling was carried out on the pathways, assessing the technological, economic and environment consequences of these plausible energy futures [24]. These models were diverse in nature in order to provide a comprehensive investigation. This multi-model approach was used to generate a broad spectrum of findings, rather than being limited to a single model. Given that the focus, and system boundaries of each model can vary significantly, their characteristics and scope were mapped in a 'landscape of models'[24].

This process was used to determine and map the breadth covered by the TP and RTP models, and identify their depth of knowledge and principal expertise. Thus, where models overlapped, insights could be checked and validated and areas lacking depth could be highlighted. The Central Co-ordination pathway was used to map out the contributions of each model [24]. An even more interdisciplinary approach was taken to explore the feasibility of the Thousand Flowers pathway. A full examination was undertaken of the technical and institutional transformation necessary to move from a centralised system to this highly distributed energy future [27]. A series of interdisciplinary workshops were held to explore the feasibility of this pathway, drawing on contributions from energy industry stakeholders and the cumulative research of the consortium. The workshops comprised researchers from across the project, including power system engineers, social scientists, energy economists and socio-technical transition scholars, along with invited speakers from community energy groups, Ofgem and external academics.

Further, a technology specific sociotechnical analysis was carried out on bioenergy technologies in the pathways; such as biomass based district heating, CHP, boilers and power stations. This study involved the identification of challenges that may impact the rate of deployment of each technology, derived from the quantification of the pathways, and then the exploration of the roles of different actors and institutions in facilitating technology penetration. This work improved system resolution for more effective technology specific policy recommendations and provided an avenue for a realistic appraisal of the level of uptake of technologies depicted in each pathway.

All issues, weaknesses and incomplete areas of the qualitative storylines and quantitative descriptions of the pathways were consolidated from all the above methods of investigation. As all methods began with the storyline, and quantitative descriptions of the pathways, it reduced ambiguity across their output allowing implications to be interpreted more readily across methods. Collectively, these findings directed the next iteration of the quantification of the pathways.

2.6 A closed loop system

The first iteration of initialisation through to verification (stages one to three) to generate a technical elaboration of the transitions pathways was a very flexible process. This allowed researchers freedom to explore their respective niches and interpret the pathways accordingly, providing greater breadth of analysis for investigation. Subsequent iterations that led from the investigation of the qualitative storylines and quantitative descriptors followed a more structured approach focussing on issues highlighted by the investigation stage. The irregularities and issues raised from across the research were consolidated in order to revise the quantification of the pathways. Each point raised was inspected, the underlying assumptions retraced, and revisions were made to the quantitative descriptions where appropriate. Revisions to the qualitative storylines were not found to be necessary.

Reduced flexibility for this stage, allowed for the quantification of the pathways to be improved without interfering with the integrity of the rest of the quantification. Again, an interdisciplinary approach was crucial to add robustness and avoid being trapped in a particular niche, but instead look across the landscape with greater certainty and confidence.

The number of iterations carried out using this proposed methodology is very much dependent on the level of detail required and resource available. Certainly, a break-even point must be reached, where the depth of knowledge from the niches is extracted, but which can also be consolidated with the wider view of the landscape. Three iterations of the quantitative descriptions were carried out in the RTP consortium in order to address weaknesses but also to update the quantification of the pathways accounting for changes in energy trends over time, for example the surprisingly rapid growth in rooftop solar photovoltaics.

Quantification of socio-technical storylines: Iterative Approach (TP/RTP)

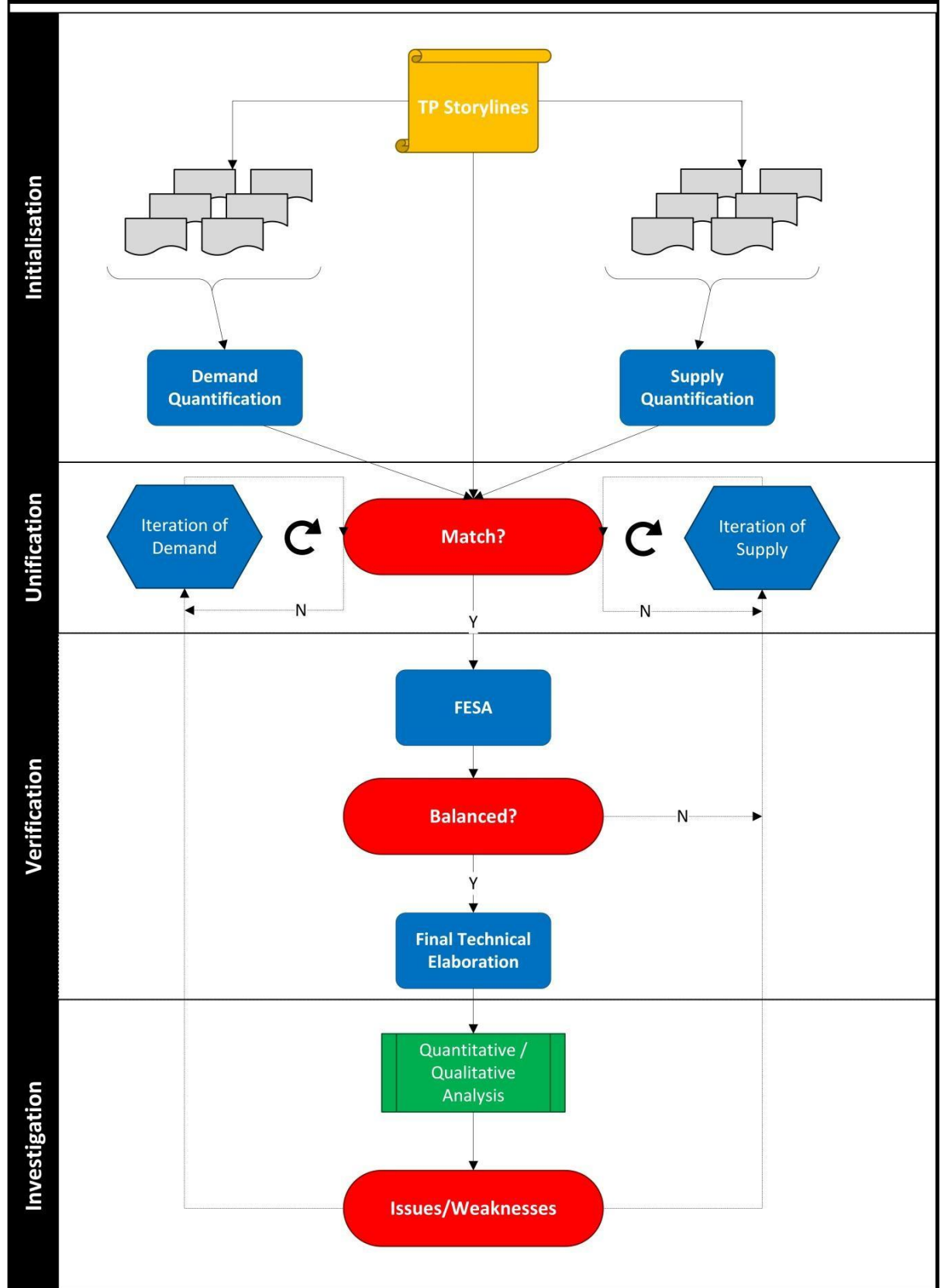


Figure 2. TP/RTP methodology framework: bridging storylines to quantitative descriptions.

3 Results from the application of proposed methodology

This section presents the development of the quantitative descriptions, and their iterations as described in the methodology. The first version of the quantitative descriptions was completed by the TEWG during the TP consortium and is labelled in the following text and graphs as 'Version 1' or 'vr 1'. The demand and supply quantifications for the Central Co-ordination can be seen in Figure 3a&b and for Market Rules and Thousand Flowers in Figure 4a&b and Figure 5a&b respectively. Version 1 results, the initial technical elaboration of the transition pathways, are presented in section 3.1 followed by a discussion of the irregularities and inconsistencies highlighted during 'Investigation', stage 4 of the process, in section 3.2.

After the investigation phase, an iteration was completed of the methodology (as in Figure 2) returning to the unification and verification stages and thus producing a revision of demand and supply quantification. The updated demand and supply quantifications for the transition pathways labelled as 'Version 2' or 'vr 2' are discussed in section 3.3 and can be seen in Figure 6a&b, Figure 7a&b and Figure 8a&b for Central Co-ordination, Market Rules and Thousand Flowers respectively. The scales on the vertical-axes of Figures 2-9 have been kept equal such that all graphs are directly comparable. It should be noted that due to a lack of disaggregated figures being available, the commercial, agricultural and transport demand are combined in to the category 'Other' in figures 2- 8.

3.1 Version 1 quantifications

Within the TP consortium the TEWG generated preliminary quantifications of the transition pathways storylines using the iterative methodology in Figure 2. A thorough initialisation stage was completed as described in section 2.2 followed by unification and verification stages as described in sections 2.3 and 2.4. Numerous iterations were completed between the unification and verification stages to ensure a balanced system that was representative of the storylines and the greater context by gathering data from a wide range of published sources and industry stakeholders' inputs. The 'Version 1' results presented here are a result of this work and were the inputs used in the investigation stage, the results from which are presented in section 3.2.

From Figure 3a, the annual demand in the Central Co-ordination pathway is observed to slowly increase from 2008 (the base year of all analysis) to 2050. The annual demand was seen to increase by 16.9% over this period, from 350.5TWh in 2008, to 409.5TWh in 2050. The demand from fuel industries and the commercial and agricultural sectors stays approximately constant over the period analysed, and a small decrease of 4.6% (5.2TWh) in demand from the industrial sector. However the domestic sector sees an increase in demand of 13.2TWh, up 11.2% from 2008 to 2050, and the electrical demand from the transport sector increases from 8.2TWh in 2010 (when disaggregated figures first appear) to 43.4TWh in 2050 – an change of +429% mainly due to the growth of battery electric vehicles and plug-in hybrids from a very small base in 2010.

The quantification of supply for the Central Co-ordination pathway is seen in Figure 3b and is itemised with respect to technology/fuel source where appropriate. Total electrical generation increases over the period from 2008 to 2050, in order to meet the rise in demand. Gas and coal plants without CCS installed are slowly phased out of the system, with no traditional coal plants running by 2035. Only one gas CCGT (Combined Cycle Gas Turbine) plant is kept open past 2035 which is used only to help meet the winter peak. Nuclear generation increases three fold, from

generating 47.67TWh in 2008 to 146.38TWh in 2050. Onshore and offshore wind generation both see an increase in installed capacity over the period leading to 52.56TWh and 63.07TWh of electricity being generated from each respective technology in the year 2050.

The Market Rules transition pathway's demand projection is shown in Figure 4a. This pathway has the largest change in demand across the set of three with an increase of 46% from 350.5TWh in 2008 to 511.6TWh in 2050. Although demand from agriculture and fuel industries remains constant there are significant increases across all other sectors. Industrial and commercial demand increase by 35.7% and 28.3% respectively over the period but the most significant changes are in the last two sectors. Domestic demand increases by 42.8%, from 117.8TWh in 2008 to 168.3TWh in 2050, and electrical demand from the transport sector increases from 8.2TWh to 45.1TWh, representing more than a fivefold increase mainly due to the growth of battery electric vehicles and plug-in hybrids from a very small base in 2010.

To meet this increase in demand, the generation profile of the Market Rules pathway also evolves and can be seen in Figure 4b. As with the Central Co-ordination pathway, all coal fired generation is phased out, along with all but one gas plant also. Both gas and coal fired CCS plants were introduced in their place. However, a larger growth of total generation from CCS plants is experienced by Market Rules with a total of 168.68TWh in 2050, compared to 94.47TWh in the Central Co-ordination pathway. The increase in nuclear, onshore wind and offshore wind generation is also stark at increases of 163%, 897% and 8576%, with 2050 generation levels being 125.07TWh, 57.75TWh and 113.21TWh in 2050 respectively. There is also an increased deployment of other renewables such as hydro, biomass, wave, tidal and solar, with a combined generation of 41.26TWh in 2050, up from 15.11TWh in 2008.

In contrast to Market Rules, the Thousand Flowers transition pathway sees a *decrease* in demand of 11.7% from 350.5TWh in 2008 to 309.5TWh in 2050 as seen in Figure 5a. The electrification of transport means that the transport sector is the only one which increases its demand in this pathway, from 8.3TWh in 2010 to 52.7TWh in 2050 – more than a six fold increase. The strongest demand decreases are from the commercial sector, down a third from 100.1TWh in 2010 to 66.5TWh, and the domestic sector, down 41.5% from 117.8TWh in 2008 to 68.9TWh in 2050.

The decrease in demand in the thousand flowers pathway means that traditional gas and coal power plants can be completely phased out by 2035 with the introduction of CCS plants. As seen in Figure 5b however, even these cleaner fossil fuelled plants have reduced output to 2050. Gas and coal fuelled plants were responsible for generating 263.58TWh in 2008 which reduces to just 24.64TWh in 2050 (11.86TWh from Coal CCS and 12.78TWh from Gas CCS). Nuclear generation is also reduced out to 2050 with a decrease in output of -58.7% while renewables (excluding CHP) increase from generating 22.21TWh in 2008 (representing 6% of electricity generated) to 131TWh in 2050 (representing 40% of electricity generated). However, the largest change in the generation scheme for the thousand flowers pathway, is the increase in electricity from CHP, with output reaching 134.63TWh by the year 2050, by which time, all of it is fuelled by renewable fuels. It should also be noted that more than 50% of electrical demand is met by smaller scale generation located in the distribution network, i.e. distributed generation.

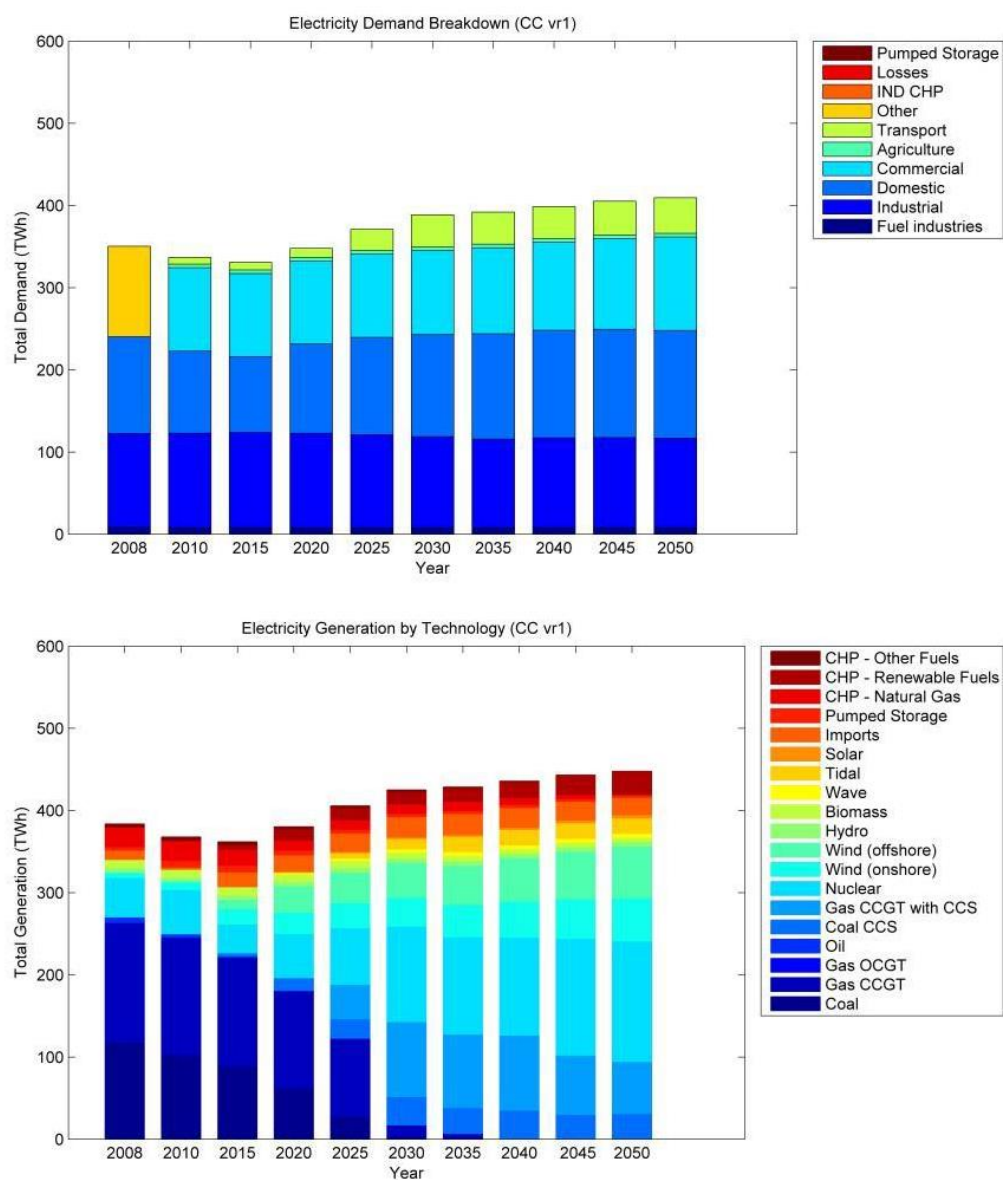


Figure 3a&b Demand and Supply Quantification for the Central Co-ordination (CC) transition pathway (vr1)

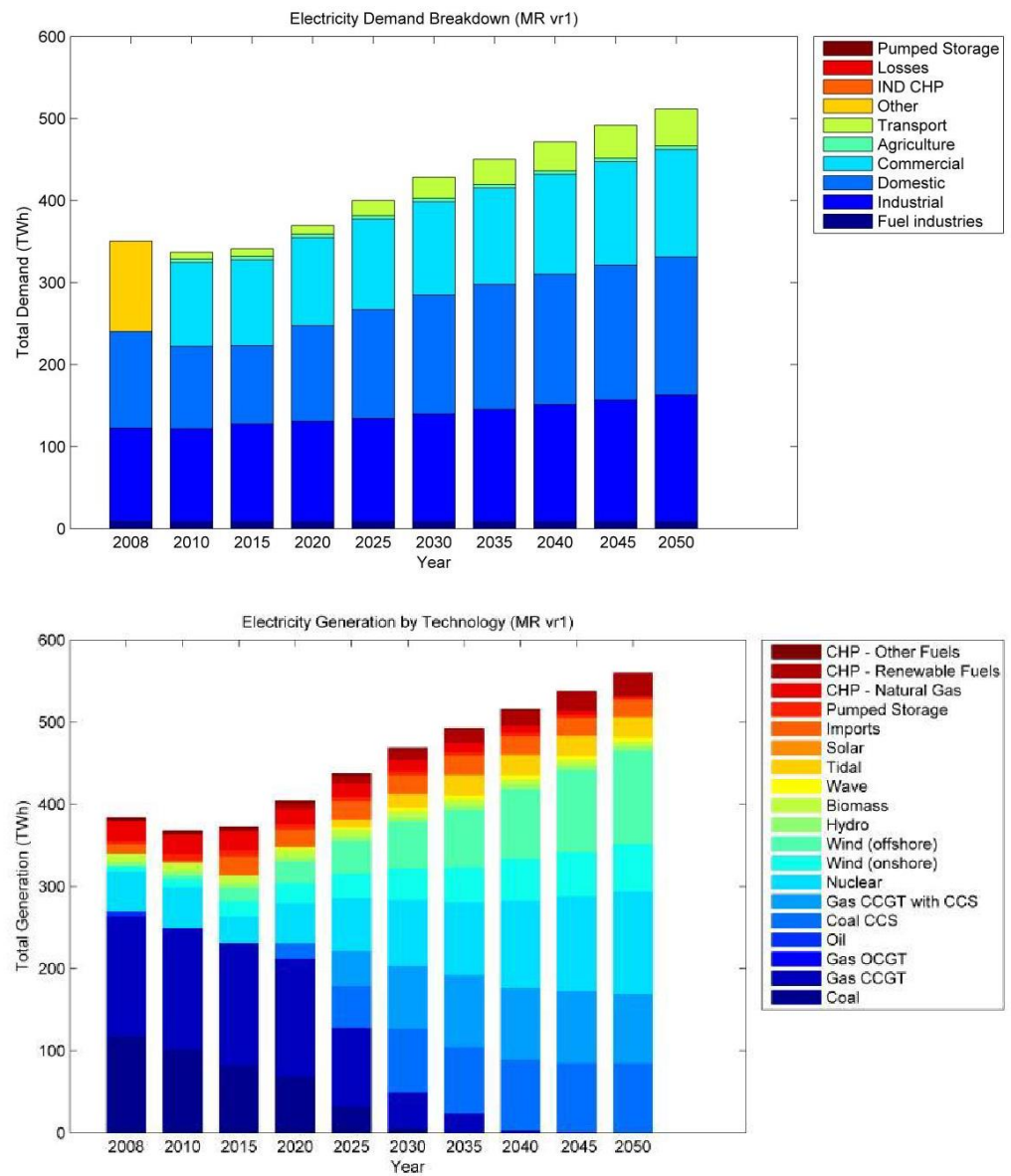


Figure 4a&b Demand and Supply Quantification for the Market Rules (MR) transition pathway (vr1)

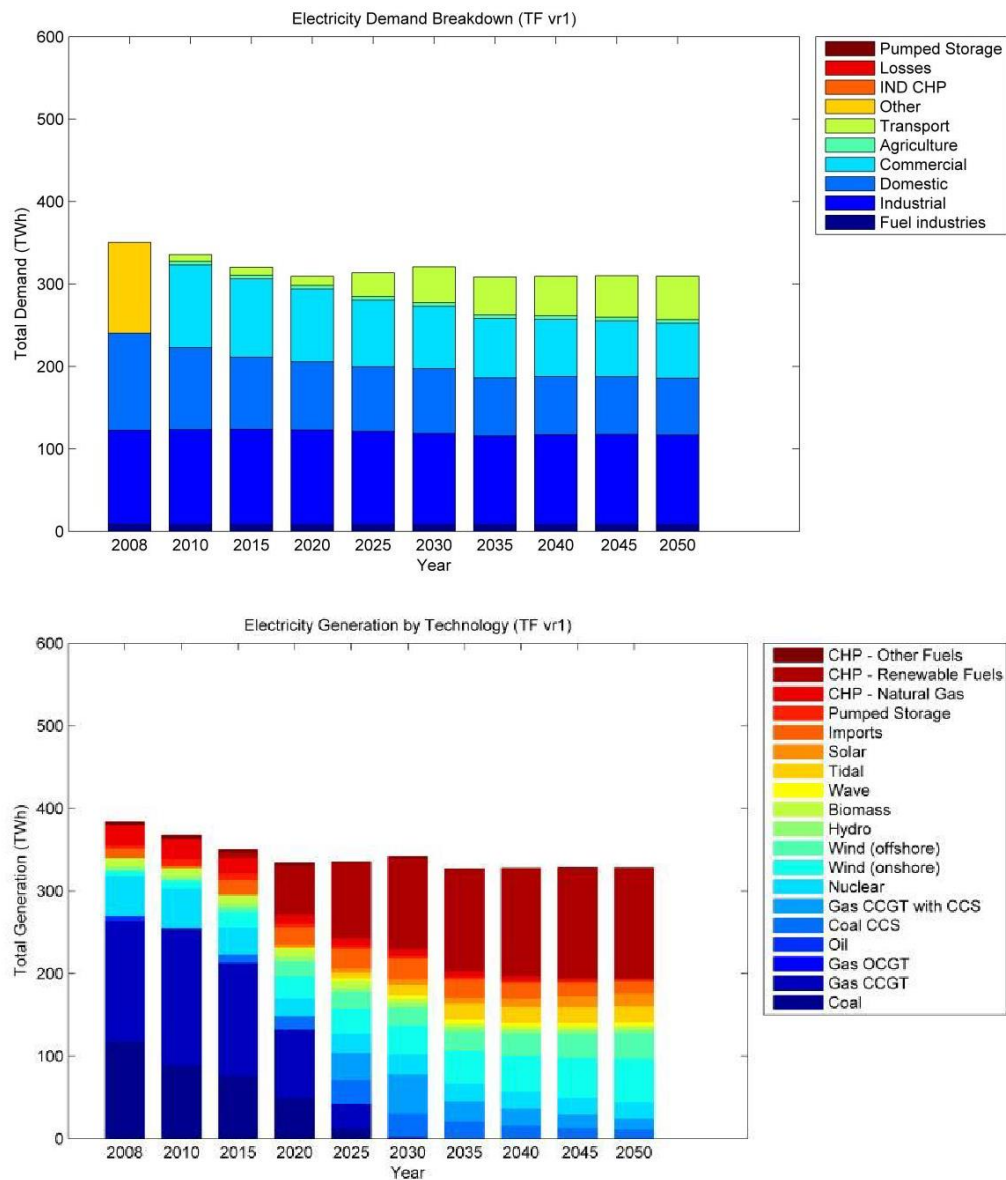


Figure 5a&b Demand and Supply Quantification for the Thousand Flowers (TF) transition pathway (vr1)

3.2 Investigation Stage Conclusions

The investigation of the qualitative storylines and quantitative descriptions of the transition pathways raised a number of irregularities and issues to be reviewed. As described in section 2.6, findings from the consortium's series of investigations were scoped, consolidated and inspected. Consolidated finding directed and necessary revisions of the storylines or descriptors in further iterations of the TP/RTP methodology framework unification and verification stages. What follows is a brief synopsis of the topics raised from the investigation stage and an account of improvements carried out in iterations of unification and verification.

Demand: what is included and what is excluded

So that direct comparisons could be made between demand and supply side figures, further categories were included in the specification of demand. Specifically, (re-calculated) transmission and distribution system losses and the demand from pumped storage generating plant were added. The result is such that any difference between demand and supply figures fully represents electricity surplus/export with no ambiguity.

Capacity factors: technical maximums and clarifications

Work conducted by Mott MacDonald [40] determined technical maximum capacity factors for a variety of generation technologies, a number of which had been exceeded in version 1 of the pathway quantitative descriptions therefore the descriptions had to be revised. Furthermore, the term 'capacity factor' as used in the pathways descriptors was ambiguous due to the lack of a standard definition found in the literature where 'capacity factor' can or cannot include self-use and maintenance penalties. The definition used in this analysis for capacity factor was therefore expressly defined as:

$$CF = A_{ave} \times LF_{ave} \times (1 - PR) \quad \text{Equation 1}$$

where CF is the capacity factor and A_{ave} the average availability of the plant, LF_{ave} is the average load factor and PR the plant power requirement (self-use).

In this analysis capacity factors have therefore been defined to include self-use and average availability to take account of maintenance etc. This removed the uncertainty raised from multiple modelling environments applying different penalties and ensured a consistency for valid comparison of results. The application of this definition across all pathways, in conjunction with maximum factors in [40], ensured the quantitative descriptions were technically feasible and consistent. As a result of this revision a number of capacity factors in the supply side descriptors were reduced and capacity of installed plant increased as necessary across the pathways.

Gas generation accounting

A fault in the accounting of gas fired industrial CHP and gas CCGT (Combined Cycle Gas Turbine) necessitated a complete overhaul of the descriptors, starting from the 2008 base year, and working forward out to 2050 for each pathway. Namely, there had been an error in the initialisation stage of the methodology with regard to historical data which was the base of projections. A portion of gas fired generation had been 'misfiled' as gas CHP in the process of re-arranging generation data from the literature to align with categories in the TP/RTP quantitative descriptors. This error had been further compounded by the transition of gas fired CHP to renewable fuel sources.

Changes were therefore made to CHP and gas CCGT capacity and capacity factor figures in all three pathways from the base year forward with work constantly referring back to the qualitative storylines to ensure compatibility. Alongside this re-accounting work, fuel sources of Industrial CHP units were reviewed, and in all pathways the plants were transitioned to renewable biogas as part of a revision of fuel use across the pathways.

Installation Rates

Since the initialisation of the version 1 descriptors in 2008/2009, installation of renewables (including onshore wind and solar) in the UK have surpassed expectations, increasing at unprecedented rates. Therefore, to reflect more recent trends, the installation rates of these technologies were increased, in order to provide more representative feasible (and in some cases likely) trajectories in to the future¹.

Micro-CHP in the Thousand Flowers pathway

Micro-CHP systems bridge the gap between demands and supply modelling as they are designed to be heat-led. However, the demand-side and supply-side descriptions had dealt with micro-CHP energy production in isolation. Therefore, the quantity of electricity produced by domestic and commercial micro-CHP units, which are included in supply-side figures, were revised. New electrical output figures were determined through the heat demand model, used in the production of the demand-side descriptors, to ensure accuracy and consistency. There was also a revision of the size of installed micro-CHP units with a new assumption that units are sized to the average heat load of a building (or buildings).

CHP Fuel sources

Industrial CHP units, across all three of the pathways' version 1 descriptors had a fuel-switching rate applied to transition from natural gas to biogas (either from waste or gasification of woody biomass). However, only the micro-CHP units in the Thousand Flowers pathway made the same switch with the micro-CHP units in the Central Co-Ordination and Market Rules pathways remaining natural-gas fuelled. This was a variance that could not be justified by analysis of the storylines or by results from the investigation stage. Therefore, as was already the case for industrial CHP units, across all pathways, micro-CHP units had a fuel-switching rate applied.

¹ With all future pathways or scenarios work there is obviously a strong desire to maintain accuracy and reflect the here and now, the world we recognise. But one must also move forward and make good use of the framing of the future that has been established, look at the insights it brings and reflect on their benefits and disadvantages. Otherwise 'scope' creep becomes the major unhelpful driver.

3.3 Version 2 Quantifications

As discussed in section 3.2, the results of the investigation stage made necessary a number of changes to the quantitative descriptors. Therefore, another application of the TP/RTP methodology as in Figure 2, namely looping back to, then iterating between, the unification and verification stages, was completed using the Version 1 quantitative descriptions and the consolidated investigation results as inputs. Below is an account of the Version 2 descriptors which were generated as a result of this work and which represent more robust and accurate quantification of the transition pathway qualitative storylines.

Version 2 demand and supply descriptions were combined into FESA time-step model using the DECC 2050 Calculator pathway representations for all non-electric energy use. The DECC Calculator added confidence that the pathways met the UK's target reductions in greenhouse gas emissions, including gases other than carbon dioxide. Market Rules suffers from just 1GW of curtailed power for 1 hour of the year in 2050, and always meets its demand. Central Coordination however has no curtailed surpluses and also always meets its demand. Thousand Flowers is extreme as it curtails some energy from 2030 onwards, of up to 22GW of power and 3.36TWh per year by 2050, but does manage to always meet electricity demand.

The quantitative descriptors produced from this further iteration and new application of the methodology can be seen in Figure 6a&b, Figure 7a&b and Figure 8a&b for the Central Coordination, Market Rules and Thousand Flowers pathways respectively. For a comparison of the changes made to the demand and supply quantitative descriptors from version 1 to version 2 see Figure 9a, b & c and Figure 10a, b & c respectively.

As seen in Figure 9a, b & c the final demand statistics have not changed between versions 1 and 2, but rather there was an inclusion of losses and pumped storage demand as identified in section 3.2. Although final demand statistics did not change there were a number of internal changes for the sake of clarity.

The specific sources of heat assumed for district heating schemes supplied by waste heat and geothermal energy were clarified, and checked for feasibility. It was specified that waste heat was derived from retrofit of heat capture technologies at existing large thermal power plants or industrial units (e.g. refineries), whilst geothermal energy was derived from heat recovered from deep aquifers. The changes were represented in quantifications of demand by introducing additional vectors 'heat transport' and 'environmental heat' for district heating and geothermal respectively.

The major technology trends of the supply mix as described in section 3.1 remained constant for all three pathways in the finalisation of version 2 of the quantitative descriptors, as can be seen in the comparison graphs in Figure 10. However, significant changes between the two versions can be seen in the gas generation and CHP categories across all pathways. These major changes were the result of a more comprehensive inclusion of industrial CHP and the subsequent re-balancing of the system that was required. Market Rules and the Thousand Flowers pathways both see a significant increase in installation rate of solar generation in version 2 over version 1, and a decrease in the installation rate of offshore wind generation more in line with current operation and practice. The divergence between the two versions for these technologies can be seen most clearly in Table 1 and Table 2.

Market Rules		2008	2010	2015	2020	2025	2030	2035	2040	2045	2050
Wind (offshore)	vr 1	1.30	5.23	16.11	26.28	39.62	56.93	70.06	85.07	100.07	113.21
	vr 2	1.30	5.23	16.11	26.28	39.19	55.51	67.51	82.13	96.57	109.14
	change	0.0%	0.0%	0.0%	0.0%	-1.1%	-2.6%	-3.8%	-3.6%	-3.6%	-3.7%
Solar	vr 1	0.02	0.02	0.04	0.09	0.12	0.15	0.18	0.18	0.18	0.18
	vr 2	0.02	0.50	1.72	2.93	4.14	4.14	4.14	4.14	4.14	4.14
	change	0.0%	96.0%	97.4%	97.0%	97.2%	96.5%	95.8%	95.8%	95.8%	95.8%

Table 1 Comparison of annual generation figures from a selection of technologies in the Market Rules pathway from versions 1 and 2

Thousand Flowers		2008	2010	2015	2020	2025	2030	2035	2040	2045	2050
Wind (offshore)	vr 1	1.30	2.48	5.67	18.40	20.15	21.90	23.65	26.28	28.91	31.54
	vr 2	1.30	2.48	5.67	18.40	20.15	21.90	22.50	23.63	24.38	25.50
	change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-5.1%	-11.2%	-18.6%	-23.7%
Solar	vr 1	0.02	0.02	0.28	2.77	5.26	6.57	7.88	10.51	13.14	15.77
	vr 2	0.02	1.96	7.78	13.61	19.44	25.26	27.20	29.15	31.09	33.03
	change	0.0%	99.0%	96.5%	79.7%	73.0%	74.0%	71.0%	63.9%	57.7%	52.3%

Table 2 Comparison of annual generation figures from a selection of technologies in the Thousand Flowers pathway from versions 1 and 2

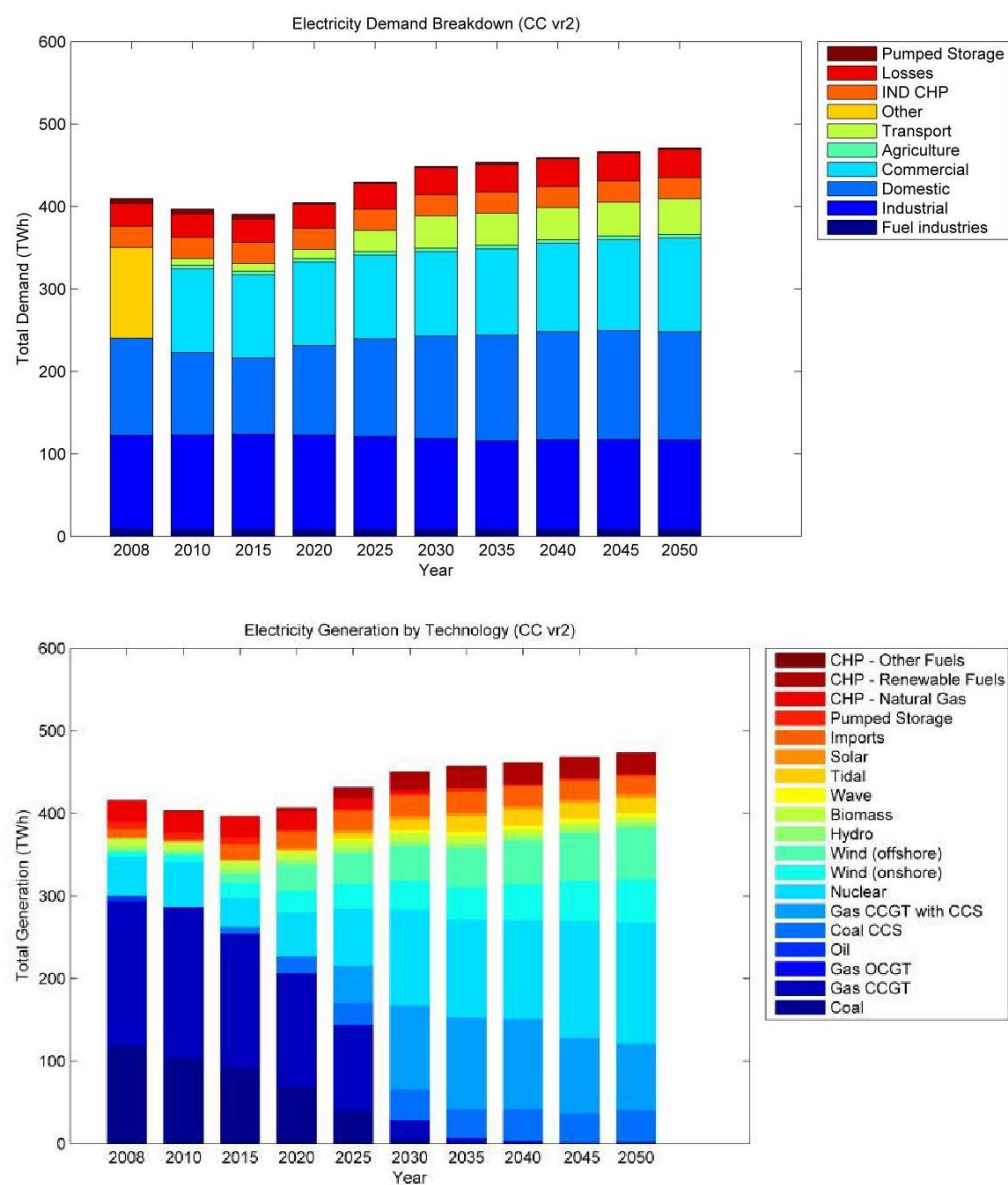


Figure 6a&b Demand and Supply Quantification for the Central Co-Ordination (CC) transition pathway (vr2)

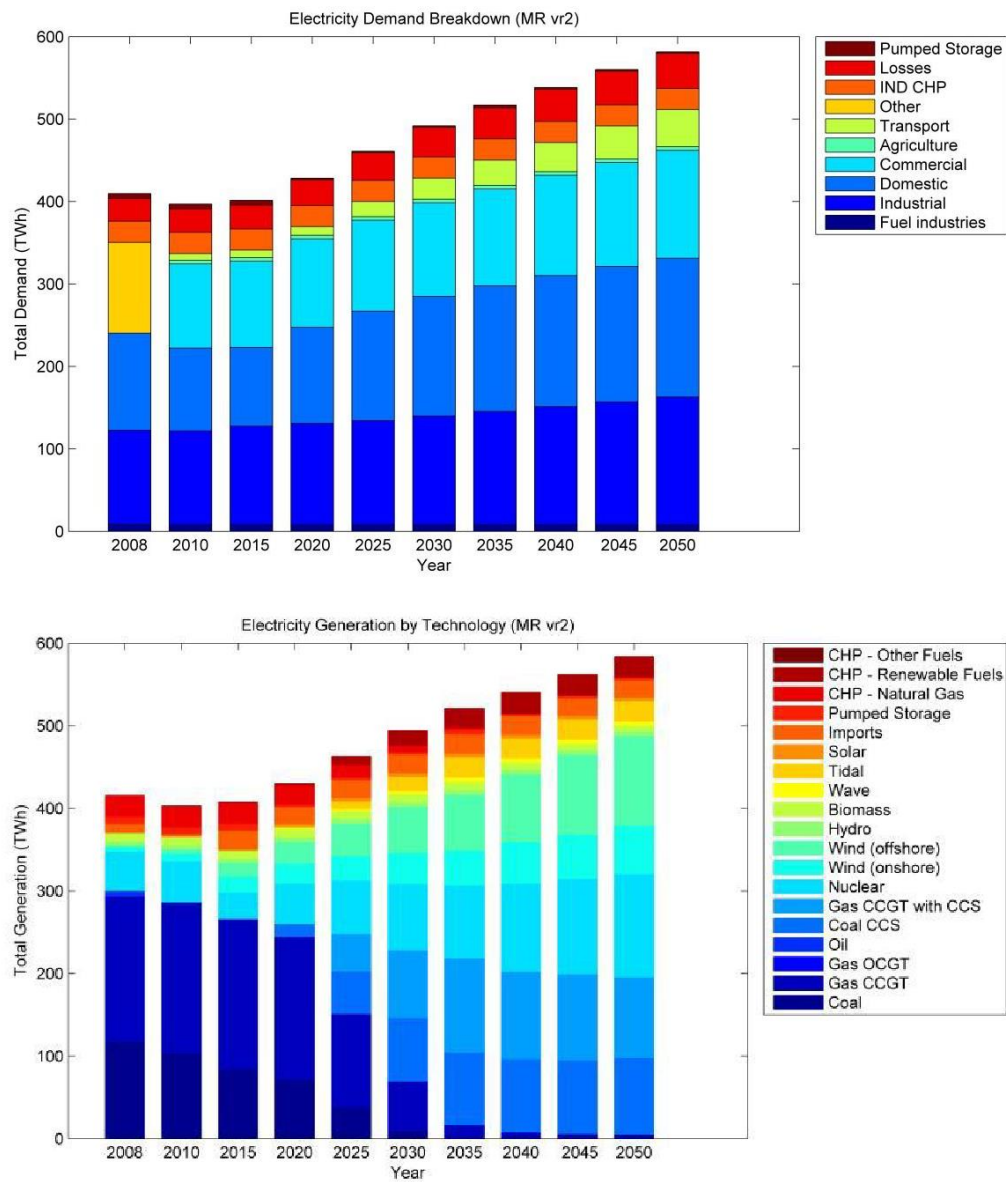


Figure 7a&b Demand and Supply Quantification for the Market Rules (MR) transition pathway (vr2)

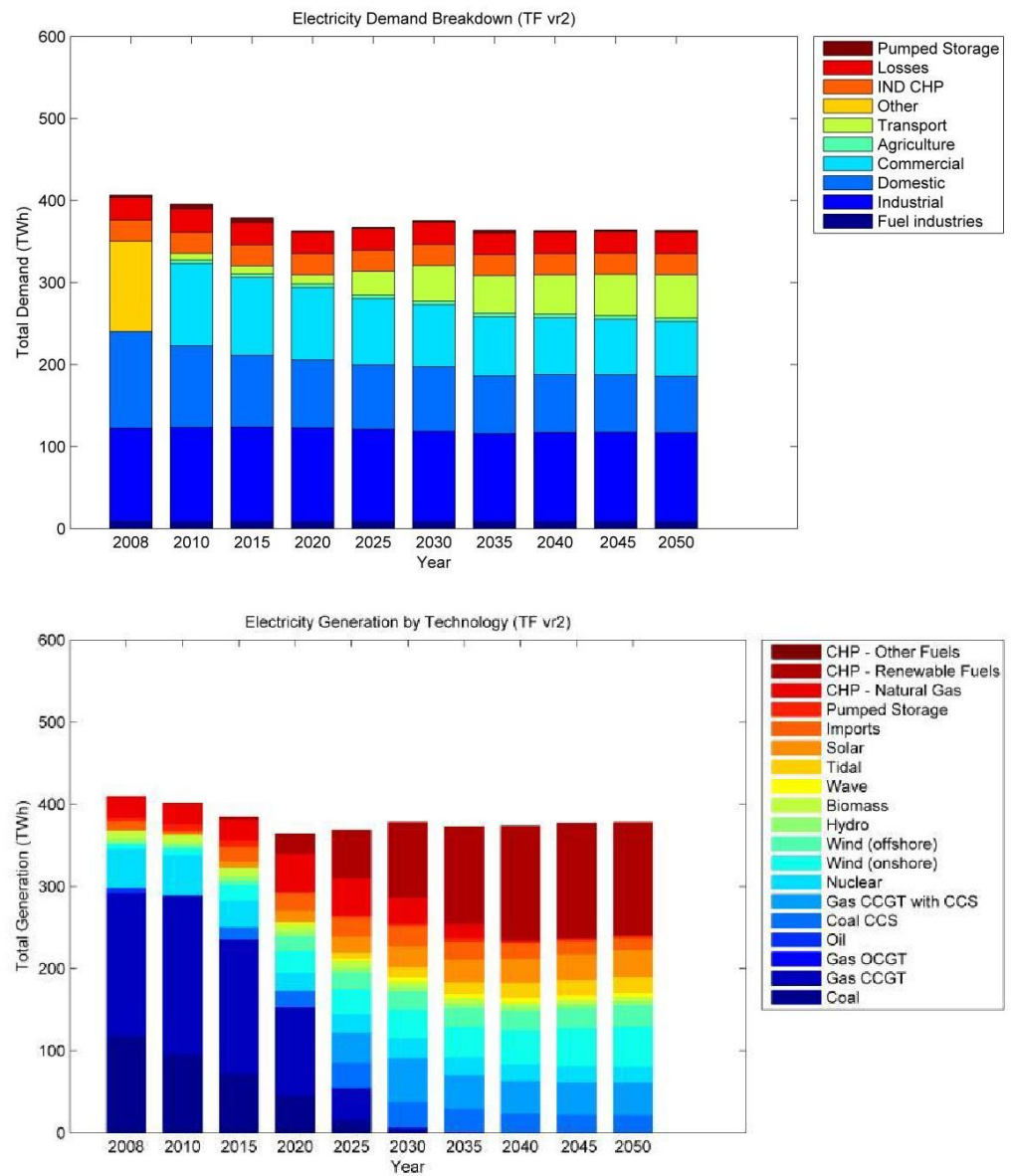


Figure 8a&b Demand and Supply Quantification for the Thousand Flowers (TF) transition pathway (vr2)

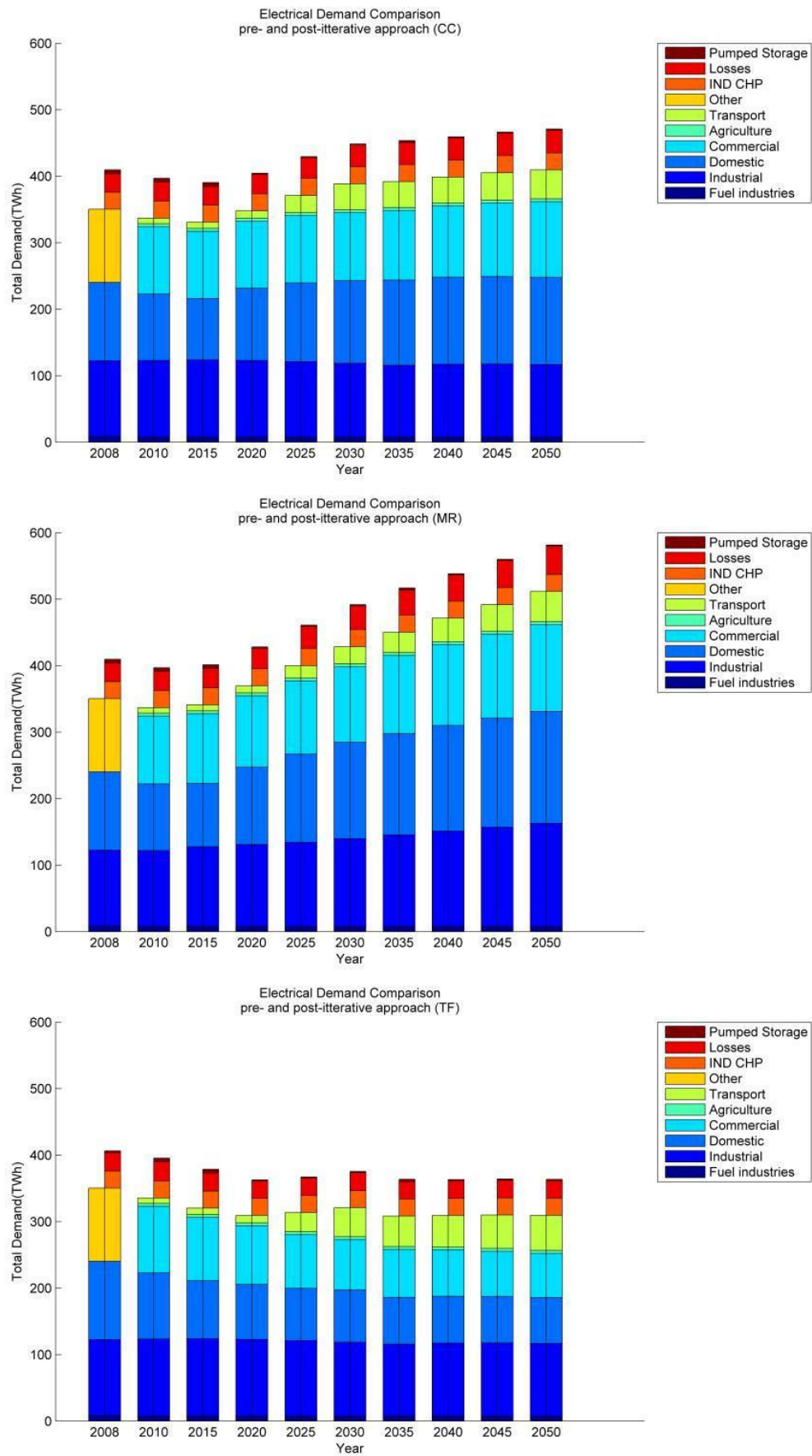


Figure 9 a, b&c Demand Quantification Comparison of vrs 1 and 2

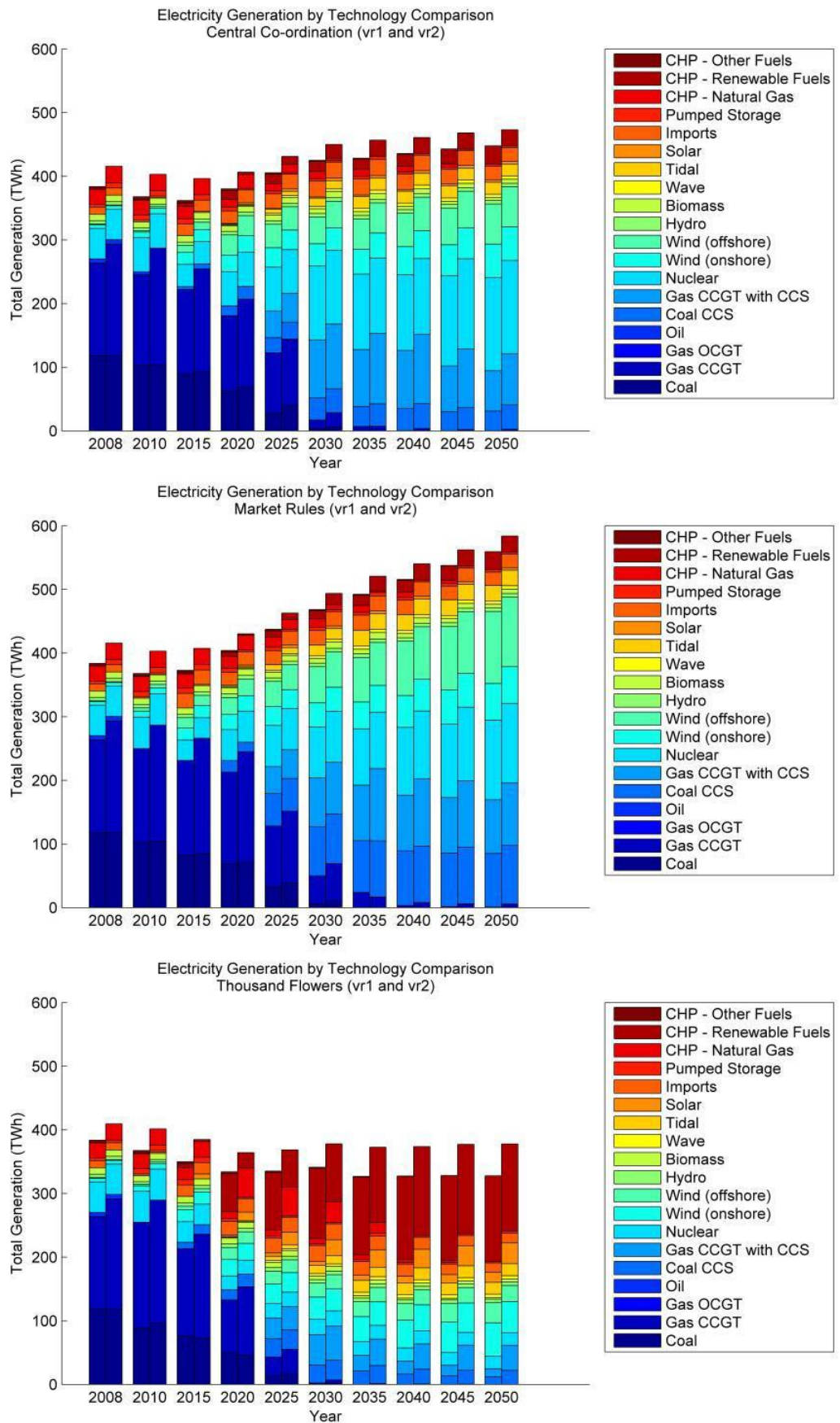


Figure 10a, b&c Supply Quantification Comparison of vrs 1 and 2

4 Discussion

The first iteration of the quantitative descriptions (version 1) of all three of the transition pathways represented balanced electrical systems. They were however the first step of the iterative process and version 2 of the descriptions were much more technically and contextually consistent. By allowing a flexible period of interdisciplinary investigation of version 1 after completion, a number of issues were addressed, which would not have been possible without the loops introduced by the iterative approach adopted. Through addressing each of the issues raised, by completing related analysis and research and altering the quantitative descriptions accordingly, the work is more technically feasible and more robust overall. This led to the development of the methodology described in this paper that has been framed around the work of the transition pathways projects. It is widely recognised that much research work in the social science, economics and engineering needs to link qualitative and quantitative work but the consistent framing of this can be difficult.

Key to realising the potential benefits of the methodology is the iterative approach adopted, to enable refinement and tuning of, in this case, three pathways. The involvement of a multi-disciplinary team and integrated working amongst them is a common set of circumstances for major collaborative research projects but drawing the domain expertise, models, data and technical language together can obviously be difficult. In a more 'traditional' project structure, you might for example expect that one group of societal domain experts would generate a set of qualitative storylines, a group of engineer experts would quantify, and in doing so raise questions of the storylines. This would go back to the societal experts for revision, and so on, but with the high likelihood that at each step, one group has only a tentative understanding of the meaning of the concerns raised by the other. Clearly a collaborative approach would be a sensible refinement to this but again it is not always the most productive. In any case, with sufficient time, such iterations might lead to robust outcomes. With the intensive and integrated approach adopted here, misunderstandings and resulting errors were rapidly identified, and meaningful and internally consistent improvements could be agreed, in a consensual and efficient way. The methodology then provided a consistent and consensual way of bringing together the correct elements, in this case the qualitative and quantitative pathways work, testing and refining them to yield an internally agreed consistent set of outputs to facilitate research work.

The verification stage is an important part of implementing the methodology. In the case of the transition pathways work there was a clear way of quantifying this, to ensure a balanced electrical system, and this was facilitated by FESA. This stage may not always be as obvious for some projects. Furthermore for the pathways a further refinement concluded that all version 2 quantitative descriptions could balance electrically and drew out a number of insights, including the various choices for the possible generation mixes and alignment with emissions targets and other pathways (e.g. DECC 2015).

A number of the changes made between version 1 and 2 (as described in section 3.3) had large impacts and knock on effects to both balancing and feasibility. This is an issue for the implementation of this proposed iterative methodology, as one may find that there are several dominant behavioural modes present. This was especially true for the pathways when addressing the accounting errors of gas-fired industrial CHP and CCGT plants, as CCGT plants were often used to cover winter peaks. Also, the increase in demand for biogas and biomass sources, due to the fuel switching of CHP units, was a concern.

These are prime examples of the potential for misunderstanding if complex scenarios are assembled in a discipline-specific or sector-specific manner. CHP plants sit on the boundary between the traditional 'demand' and 'supply' sides of the energy system. In the assembly of the first set of pathway descriptions the demand-side team and the supply-side team each believed they had addressed CHP, but did so in their own way and using different data sources. Outwardly, no problems were evident, but with further interrogation these proved to be inconsistent and incomplete. Collaborative work in the second iteration of the methodology to create the version 2 descriptors was able to address these problems rapidly and conclusively.

As well as increased technological feasibility and ensured system balancing, versions 2 of the quantitative descriptions were also seen as being more 'true' to the individual pathways' ethos'. This was due to the greater time for reflection that the iterative approach allowed, during which some further differentiation between the quantification of the pathways could be introduced. Similarly, the flexibility of the iterative approach permitted the quantification of the thousand flowers pathway to evolve freely, resulting in a far more innovative (or brave) pathway. As [41] shows, thousand flowers is an outlier in the field of GB energy system scenarios. Technically feasible quantitative descriptions such as those for thousand flowers would never evolve from a purely technical starting point and neither would they be delivered by purely a socio-political research team. It was the iterative, interdisciplinary nature of the processes shown in Figure 2 that allowed for its determination. The thousand flowers pathway quantitative description is therefore a perfect example of the strength of the technical elaboration of the storylines.

The interdisciplinary and iterative working methods of the quantification process and of the TP and RTP consortia not only improved the quality of research and its published outputs but also improved the understanding and capabilities of the individuals within the team, turning a multidisciplinary team into an interdisciplinary team.

5 Conclusions

This paper has proposed a new approach to whole systems analysis and scenario development that helps reconcile qualitative storylines and quantitative descriptions through the development of a structured methodology.

The wider scope of investigation facilitated by this interdisciplinary approach allows for a coherent first stage of initialisation to act as the bedrock of study. As demonstrated in the context of results from the elaboration of the transition pathways storylines, the further stages of unification, verification and investigation permits the quantification of well-rounded descriptors which benefit from a breadth of domain expert knowledge, from a number of fields, all with an appropriate depth. The *version 1* results from the first set of iterations demonstrated balanced energy system quantifications which were used as a consistent base for storyline analysis in the Transition Pathways consortium.

The iterative nature of the methodology is a key element that enables refinement whilst allowing contributors to individually and collectively gain insights from the qualitative and quantitative analysis. Therefore, in the case considered in the paper the methodology provided a framework for the revision of descriptors leading to the *version 2* descriptors which were more accurate, consistent and robust than those determined previously. Simultaneously, the iterative, and therefore evolutionary, nature of the elaboration methodology allowed for more innovative (brave) scenario developments that are free from the constraints of the current regime and discipline specific norms but remain grounded.

This proposed methodology for the quantification of qualitative storylines is, to the best of the authors' knowledge the first of its kind to reconcile qualitative and quantitative scenario descriptors. Its application, both within the energy sector and to other fields with supply and demand, to the elaboration of future-orientated research (i.e. scenarios) would be advantageous.

Acknowledgements

This work was conducted as a part of the Realising Transition Pathways project, supported by the UK Engineering and Physical Sciences Research Council (Grant EP/K005316/1). The funding source was not involved in the study or in writing this paper. The authors thank the other members, especially Evelina Trutnevyte, of the Realising Transition Pathways and the preceding Transition Pathways projects, who developed the transition pathway storylines and participated in technical elaboration (then collaboration) groups.

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7.6 Key Outputs

An iterative approach was presented in this paper to quantify the pathways (accounting for their socio-political drivers), to produce quantitative descriptions that are coherent and consistent with the qualitative storylines. This interdisciplinary methodology allowed all three pathways to be investigated, greatly enhancing the understanding of the potential development of the UK power sector under these three decarbonisation frameworks (as set out in objective 4 of this thesis). Subsequently, the following necessary improvements were performed in order to increase the robustness of the pathways:

- The system boundaries of supply and demand were matched up to allow direct comparison.
- Capacity factors were corrected, and in some cases generation capacity was increased.
- Changes were made to gas combined cycle gas turbine (CCGT) and gas CHP capacity and capacity factor to correct a miss translation of generation data in the original quantification of the pathways.
- Improved installation rates of renewable technologies, reflecting trends in the current market since the original elaboration of the pathways.
- Inconsistent modelling of gas CHP across pathways was rectified and a consistent fuel switching rate was applied to account for the switch to biogas.

The result was a more coherent and robust quantification of all three pathways, for which their qualitative storylines and quantitative descriptions were fully reconciled. The resulting upgraded quantitative descriptions form the basis of the future energy and environmental assessment of the pathways. This methodology could offer guidance to the number of growing interdisciplinary projects worldwide, which bring social scientists and energy modellers together, to build more robust future scenarios.

8 Article V – ‘Indicative energy technology assessment of UK shale gas extraction’

8.1 Journal Paper

G. P. Hammond and Á. O'Grady, 2016. *'Indicative energy technology assessment of UK shale gas extraction'*. *Applied Energy*, in Press.

<http://dx.doi.org/10.1016/j.apenergy.2016.02.024>

8.2 Contribution to Research:

The adoption of shale gas production in the UK could fundamentally re-order the Nation's energy policies, and alter the direction of the future energy system. However, shale gas and its associated extraction activities have generated much community resistance and controversy. Literature deliberating over shale gas adoption is often driven by a set agenda, either supporting, or opposing the introduction of the technology. This paper draws up an objective set of debits and credits for shale gas fracking, based on analysis rather than advocacy, in order to contribute to the ongoing national dialogue. This analysis is aimed at illustrating the consequences of shale gas fracking within a UK setting against a backdrop of imperfect, and sometimes contradictory, information.

The introduction of a new electricity generator comes with a unique set of environmental impacts which must be quantified and managed. The potential environmental impact of shale gas extraction and its use for electricity generation are analysed in this paper; contributing to the delivery of objective 5 in this thesis. An energy technology assessment was undertaken, employing a 'balance sheet' approach so as to examine the advantages and disadvantages associated with shale gas production in the context of the UK energy future. The economic, environmental, safety and social repercussions of shale gas technology adoption were explored. Such an assessment provides a valuable evidence base for communities, developers, policy makers, and other stakeholders.

8.3 The Significance and Originality of the Article

An impartial assessment of the positives and negatives regarding the introduction of shale gas extraction, contextualised to the UK situation is presented in this journal. In contrast to other publications in this area, the most critical facts and evidence were scrutinised applying strong academic rigour, free from any bias or advocacy. A wide variety of reports and media outputs have been published often laden with bias either endorsing or chastising the introduction of this technology. This piece represents a much needed unbiased synopsis of the current thinking of the economic, environmental, safety and social repercussions of shale gas extraction in the UK. This paper will equip both energy stakeholders and the wider public with a deeper understanding of the most important considerations in light of a budding shale gas industry in the UK.

8.4 Contribution by Candidate:

Second author (generating 45% of content)

The candidate was predominately responsible for the concept and drafting of section 4, 5, 6, and 8. These sections encompassed research relating to the environmental concerns associated with shale gas extraction. Additionally, the candidate contributed to the other sections as required. The candidate completed a full critical revision of the paper, and provided updates in response to a fast moving political landscape. The candidate also helped address various reviewer comments, particularly pertaining to the environmental concerns discussed.

Indicative energy technology assessment of UK shale gas extraction

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ABSTRACT

There is at present much interest in unconventional sources of natural gas, especially in shale gas which is obtained by hydraulic fracturing, or 'fracking'. Boreholes are drilled and then lined with steel tubes so that a mixture of water and sand with small quantities of chemicals – the fracking fluid – can be pumped into them at very high pressure. The sand grains that wedge into the cracks induced in the shale rock by a 'perforating gun' then releases gas which returns up the tubes. In the United Kingdom (UK) exploratory drilling is at an early stage, with licences being issued to drill a limited number of test boreholes around the country. But such activities are already meeting community resistance and controversy. Like all energy technologies it exhibits unwanted 'side-effects'; these simply differ in their level of severity between the various options. Shale gas may make, for example, a contribution to attaining the UK's statutory 'greenhouse gas' emissions targets, but only if appropriate and robust regulations are enforced. The benefits and disadvantages of shale gas fracking are therefore discussed in order to illustrate a 'balance sheet' approach. It is also argued that it is desirable to bring together experts from a range of disciplines in order to carry out energy technology assessments. That should draw on and interact with national and local stakeholders: 'actors' both large and small. Community engagement in a genuinely participative process – where the government is prepared to change course in response to the evidence and public opinion - will consequently be critically important for the adoption of any new energy option that might meet the needs of a low carbon future.

KEYWORDS: : Shale gas; hydraulic fracturing; resources; economic and environmental impacts; induced seismicity; public acceptance; regulation

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1. INTRODUCTION

1.1 Background

Human development is underpinned by energy sources of various kinds that heat, power and transport its citizens in their everyday life. But all energy technologies have unwanted ‘side-effects’; they simply differ in their level of severity. Hydraulic fracturing, or ‘fracking’, for shale gas is a particularly controversial energy option that is receiving significant development support from government in the United Kingdom (UK). Licenses have been issued by the *Department of Energy and Climate Change* (DECC) to drill a limited number of test boreholes around the country (see, for the case of England, [1]). These boreholes are then lined with steel tubes, and a mixture of water and sand with small quantities of chemicals – the fracking fluid - is pumped into them at very high pressure. The sand grains that wedge into the cracks induced in the shale rock by a ‘perforating gun’ then releases gas which returns up the tubes (see Fig. 1). The UK Government is attracted by the possible benefits of securing large quantities of shale gas for the UK as an energy ‘game changer’: leading to a potential ‘Golden Age of Gas’, according to the *International Energy Agency* (IEA) [2]. The IEA sees shale gas as contributing about 14% to global gas production by 2035.

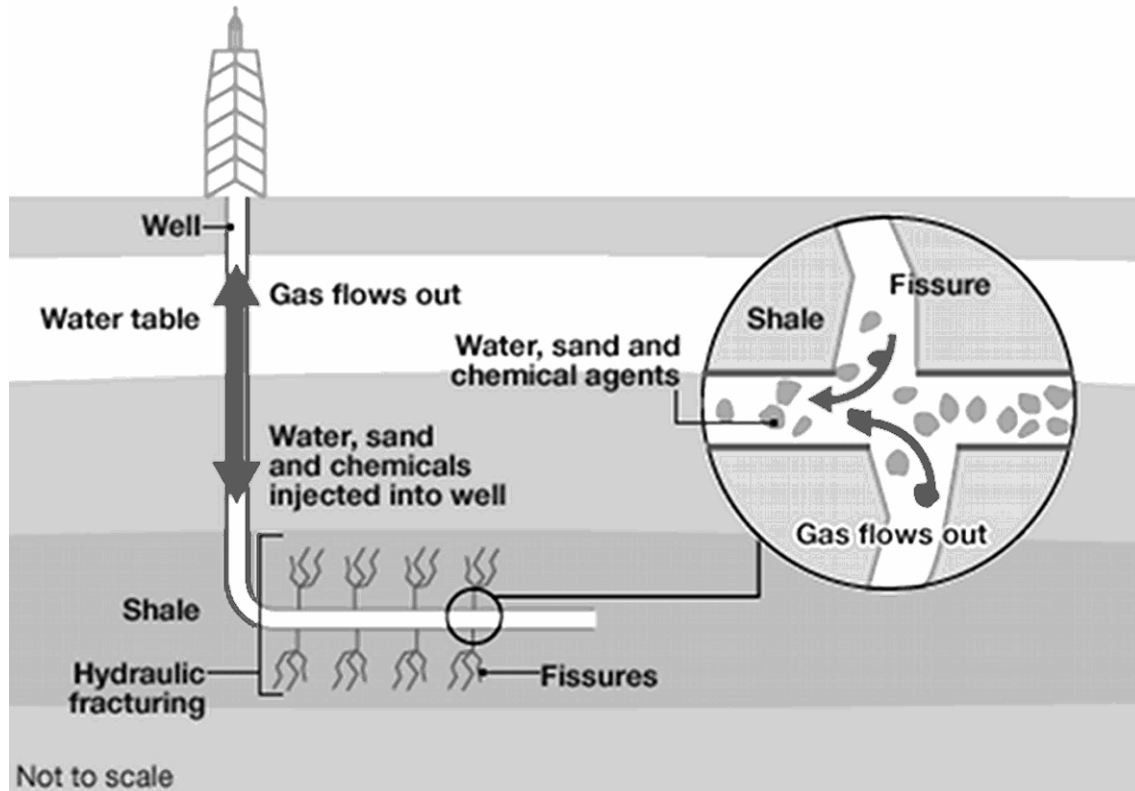


Fig. 1. The shale gas 'fracking' process (*Source: adapted from Transition Haslemere.*)

However, the exploitation of fracking will involve a range of advantages and disadvantages ('credits and debits') that will fall disproportionately on different sections of British society. So it is necessary to identify the components of a shale gas fracking 'balance sheet' of the sort employed in technology assessment [3-5] in order to evaluate its impact on communities, countryside and wildlife, and to determine whether it is compatible with Britain's move towards a low carbon future in 2050 and beyond.

1.2 Historical Development of Fracking for Shale Gas

The technique of hydraulic fracturing began in the United States of America (USA) [6] in around 1949 when the first two, small-scale commercial vertical wells were initiated in Oklahoma and Texas respectively [7,8]. But it was not until about 1997 that the process known as 'slickwater fracturing' was developed and implemented in the Barnett Shale by the then *Mitchell Energy*. This is a method that involves adding chemicals to water to increase the flowrate at which the fracking fluid can be pumped down a well-bore to fracture extremely dense shale. The fracking fluid is made up of around 98.50% water, 1.00% sand, and 0.05-0.50% chemical additives [6]. These chemicals are friction reducers, usually a polyacrylamide, together with biocides, surfactants and scale inhibitors. Biocides prevent organisms from blocking the 'downhole' and fissures, whereas surfactants keep the sand grains in fluid suspension. Other chemicals that are sometimes employed include benzene, chromium, and a number of other compounds [6]. North American fracking companies keep the composition of this chemical 'cocktail' secret, claiming commercial confidentiality, although an independent study identified about 650 separate chemicals compounds. However in the UK, companies are obliged, under the *Water Resources Act* 1991, to disclose the composition used. Many of these are known to be toxic and widespread concern has been expressed over potential water contamination [6, 9-11]. Nevertheless, it was this pressure-induced slickwater fracturing (see again Fig. 1) that made shale gas extraction economical by radically reducing the costs of horizontal fracking [6].

The situation with shale gas development in the UK is quite different from that in the USA, where some 200,000 horizontal gas fracking wells have been in operation over the last two decades or so (Prof. Will Fleckenstein, Colorado School of Mines, USA, private communication 06.11.15) in comparison to just one in Britain - at the Preese Hall site in Lancashire. In addition, the regulatory framework is likely to be tighter in the UK, e.g., 'flowback water' will not be permitted to be reinjected into wells. Environmental limits are also uniformly established across the UK and adherence monitored by national regulators. Water use in the United States (US), by contrast, is regulated on a State-by-State basis.

1.3 The Issues Considered

The possible benefits and disbenefits of shale gas fracking include economic, environmental, safety and social consequences [12] for the UK. Here they are discussed as an example of a

‘balance sheet’ approach: analysis rather than advocacy. In order to draw up an objective and rigorous set of credits and debits for shale gas fracking (or indeed other potentially ‘disruptive’ technologies) as part of a national dialogue, it is argued that is desirable to bring together experts from a wide range of disciplines to undertake *energy technology assessments* (ETA) [5] that exhibit balance, objectivity and broad public participation. This should draw on and interact with national and local stakeholders: ‘actors’ both large and small. Community engagement will consequently be critically important for the adoption of any new energy option that might meet the needs of a low carbon future. This contribution is part of an ongoing research effort aimed at evaluating and optimising the performance of various sustainable energy systems (see, for example, Hammond *et al.* [13] and Hammond and Hazeldine [14]) in the context of transition pathways [15,16] towards the statutory target of a reduction in UK ‘greenhouse gas’ (GHG) emissions by at least 80% by 2050 from 1990 levels [17]. It is aimed at illustrating the consequences of shale gas fracking within a UK setting in the light of imperfect, and sometimes contradictory, information. Nevertheless, such assessments provide a valuable evidence base for communities, developers, policy makers, and other stakeholders. They also yield lessons for other European countries attempting to extract significant quantities of shale gas whilst attempting to decarbonise their energy systems, although local circumstances will obviously limit the wider applicability of the present findings.

2. THE POTENTIAL SHALE GAS RESOURCE IN THE UK

On the positive side of the ‘balance equation’ is the prospect that fracking could potentially yield significant quantities of shale gas to meet the Britain’s energy needs. In contrast (on the negative side), the IEA [2] warn that the significant global development of this gas would put the world on a trajectory towards a long-term temperature rise of over 3.5°C; well above the widely suggested ‘safe’ level of 2°C. The *British Geological Survey* (BGS) [18] has estimated the possible reserves of shale gas in the *Bowland-Hodder* study area or ‘play’ (encompassing national parks and major cities) and the Weald in the South East for DECC: see Fig. 2.

Bassi *et al.* [19] have also collated several estimates of UK shale gas potential that are presented in Table 1. The great uncertainties inherent in such provisional estimates [total UK technically recoverable shale gas reserves of 150 – 1,130 billion cubic metres (bcm)] can only be refined by extensive investigative drilling, possibly requiring hundreds of wells [19,20]. Notwithstanding the differences between these estimates, they suggest that UK resources are likely to be significant compared to those elsewhere in Europe; given the moratorium on shale gas fracking in France and the limits on extraction in Poland, due to geological constraints [Prof. Danny Reible, Texas Tech University, USA, private communication 05.11.15].

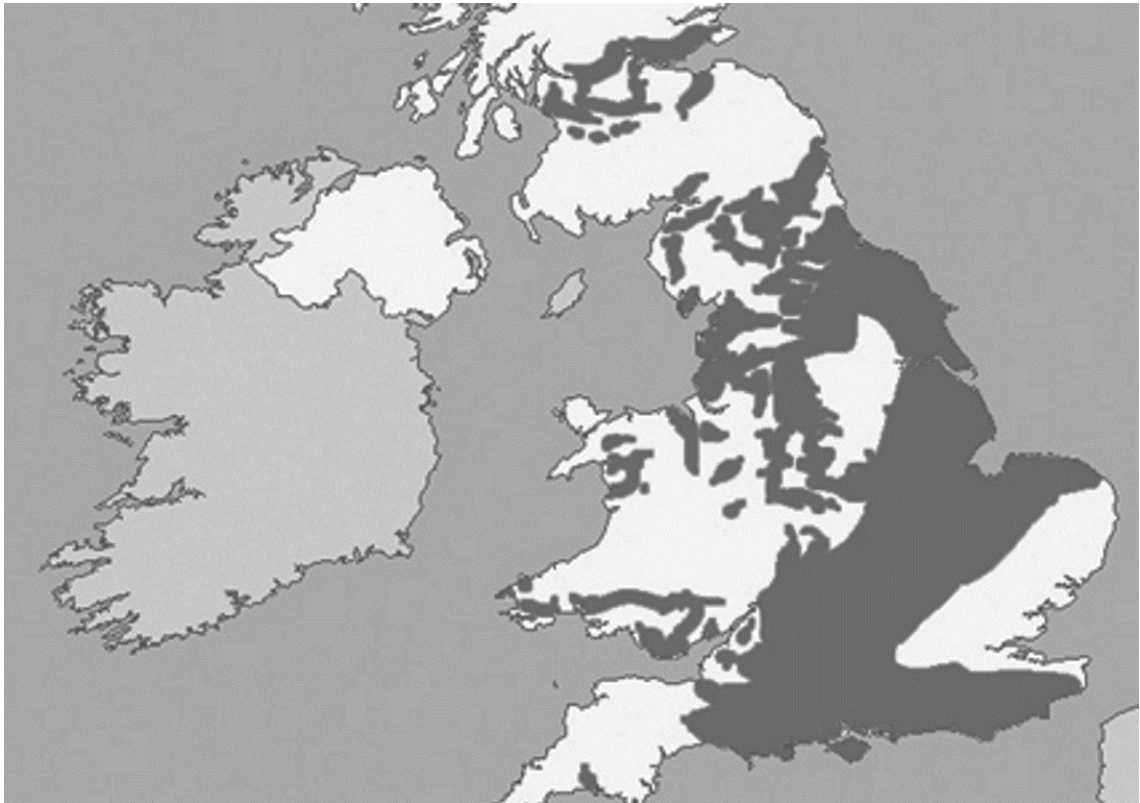


Fig. 2. Potential UK shale gas reserves [sites - dark shading] (Source: adapted from *Standpoint* magazine, April 2012; after BGS [17].)

Table 1. Estimates of shale gas potential in the UK (bcm)

		EIA	BGS/DECC	Cuadrilla	ECC
Bowland Shale	Gas in place	2,690	-	5,660	-
	Technically recoverable	540	80 - 200	900-1,200	60 - 110
Weald Basin (Liassic shale)	Gas in place	60	-	-	-
	Technically recoverable	30	-	-	-
Total UK	Gas in place	2,750	-	-	-
	Technically recoverable	570	150	-	1,130

Sources: various estimates collated by Bassi *et al.* [19]: US Energy Information Administration (EIA); Cuadrilla Resources – a UK unconventional gas exploration company; British Geological Survey (BGS); UK Department of Energy and Climate Change (DECC); Energy Contract Company (ECC) – a UK-based commercial oil and gas consultancy.

Timescale of estimates: 2011-2012 Units: billion cubic metres (bcm)

However, making assumptions about recovery rates (based on experience at over 80,000 US horizontal shale gas fracking sites) and the proportion of available resources extractable in the UK, the BGS suggest [18] that recoverable shale gas resources might be equivalent to some 25-50 years of current UK natural gas (NG) demand. That would significantly contribute to Britain's energy security and independence. However, making full use of this resource may not adhere to UK carbon budgets [21] and could risk missing its legally-binding 2050 GHG emissions reduction target.

3. SHALE GAS SOCIO-ECONOMIC AND MARKET ISSUES

The UK balance of payments would obviously benefit significantly from the large-scale development of shale gas extraction, although it is unlikely that gas bills for household and industrial consumers would fall dramatically as they have done in North America. This is because the USA is effectively a “natural gas island” with very limited ‘Liquefied Natural Gas’ (LNG) imports via the gas trading hubs of Europe [22]. In the USA, supplies of conventional NG have been drying up, and unconventional gas (including from shales) has been able to grow rapidly to meet some 60% of marketed production, according to the IEA [2]. Many US energy analysts believe that this fall in gas prices to historically low levels has been caused by advances in extraction techniques, particularly fracking, driving down production costs. Much of this shale gas production occurred as an almost ‘free’ co-product of unconventional oil extraction. In contrast, the UK is part of the wider European natural gas market [23] where the gas price is determined by the supply and demand for indigenous natural gas, imports from Russia, and LNG from North Africa and Middle East. Shale gas supplies in the UK will only provide a small fraction of those in this wider gas market. So the household economic benefits in Britain are therefore unlikely to live up to the hopes of the UK Prime Minister (David Cameron), who argued in the *Daily Telegraph* newspaper (11/08/13) that it would “see lower energy prices in this country”. The British *House of Commons’* Energy and Climate Change Committee [24] argued that domestic shale gas production could reduce the risk that prices would be determined over the longer term by imports (either via natural gas pipeline or by way of LNG). Nevertheless, they concluded that there is substantial uncertainty over the impact of unconventional gas extraction on market prices. David Cameron also cited job creation as another socio-economic benefit. That will undoubtedly follow successful shale gas exploitation, but it is unclear whether this would be any greater than for equivalent programmes aimed at supporting the adoption of energy demand reduction measures (such as thermal insulation or high efficiency lights and appliances) or small-scale low carbon energy options.

A *Task Force on Shale Gas* (TFSG) was established in the UK in September 2014 funded by several companies with commercial interests in the oil, gas and chemicals sectors [*Centrica, Cuadrilla Resources, Total, The Weir Group, GDF SUEZ E&P UK Ltd., and the Dow Chemical Company* (until September 2015)]. It was led by the former chair of the *Environment Agency* for

England and Wales (Lord Chris Smith) with three other ‘independent’ panel members. However, environmental *non-governmental organizations* (NGOs), such as *Friends of the Earth*, and various local anti-fracking protest groups have expressed skepticism about its claimed impartiality. Nevertheless, it is useful to compare and contrast the findings of the Task Force with those of the present ETA study. Its last report [25] dealt with the potential economic impacts of shale gas extraction in Britain. The TFSG acknowledged at the outset that it is difficult to judge these effects given the uncertainties around the potential availability of shale gas in the UK. In any event, they recognised that such shale gas extraction would have only a minimal impact on the European market for similar reasons to those suggested above. They therefore recommended the drilling of a number of exploratory wells in order to gain a clearer picture of recoverable shale gas in Britain. Despite the uncertainties, they went on to argue that job creation might amount to thousands of jobs directly and many more in the wider supply chain [25], rather in line with the British Prime Minister’s assertion noted above. However, the ‘*Campaign against Climate Change*’ Trade Union Group has estimated (backed by eight national unions and aided by six academic specialists) that far more jobs could be generated via equivalent investment in developments that would mitigate GHG emissions [26]. These ‘climate jobs’ would be created from the adoption of energy conservation measures in the home and in public buildings, renewable energy technologies, clean public transport, and in the development of ‘green skills’ that will be required through education and training. Based on case studies on the Fylde (the coastal plain in western Lancashire, northern England) and in Salford (a metropolitan borough of Greater Manchester) they suggest that climate jobs could amount to some 14 times those produced directly from the fracking sector and 80 times nationally, i.e., including indirect employment creation across the supply chain. [A breakdown of the one million ‘climate jobs’ that might be generated by 2030 are shown in Table 2. In addition, Neale [26] argues that half a million additional, or ‘spin-off’, jobs could also be created.] Such figures are only indicative, although they provide an important contrast to official rhetoric from David Cameron and others about the prospects of employment creation from shale gas fracking.

Perhaps the most important socio-economic issue concerns the distribution of the benefits and costs of shale gas fracking between various communities and demographic groups. Depending on how much shale gas can be exploited, the UK overall could benefit from improved energy security and reduced balance of payments, but it is local communities that will bear most of the risks associated with fracking. The Government intends to offset this potential harm by encouraging (but not requiring) the extraction industry to sign up to a charter that will guarantee payments of some £100,000 to communities located near shale gas exploratory wells. If the gas is ultimately exploited, then they would receive one *per cent* of the resulting revenues: it has been suggested that this might amount to some £10 million.

Table 2. Estimates of potential ‘climate job’ creation in the UK

Electricity	400,000
Transport	310,000
Buildings	185,000
Industry	25,000
Education	35,000
Agriculture, Waste and Forestry	45,000
Total UK ‘Climate Jobs’	1,000,000

Source: Neale [26]. A companion technical report is available online [http://www.campaigncc.org/sites/data/files/Docs/online_companion_nov_2014.pdf].

Timescale of estimates: job creation over the period to 2030

Others have proposed the creation of some form of ‘*Sovereign Wealth Fund*’ (analogous to that generated from Norwegian North Sea oil and gas revenues) to recompense affected UK regions and communities. It is obviously too early to tell how attractive such financial incentives might be to local communities. The *Task Force on Shale Gas* [25] have recommended that operators explain precisely how they intend to provide the £100,000 of local community payments for exploratory well pads and that the beneficiaries should be clearly defined. Properties directly affected by producing wells would obviously face the greatest disruption. The TFSG [25] therefore believe that there should be community involvement in the development of a “fair and robust” community payments scheme.

4. INDUCED SEISMICITY

Great public concern over shale gas fracking was triggered in 2011 by two seismic tremors, or minor earthquakes (largest reaching ~ 2.3 M_L; the local magnitude on the *Richter scale*), caused by exploratory drilling at the *Cuadrilla Resources* site at Preese Hall near Blackpool. Consequently, a moratorium was temporarily placed on shale gas exploration in the UK. Subsequent studies by DECC [27], aided by independent experts, together with a review of the scientific and engineering evidence on shale gas extraction undertaken by the *Royal Society* (RS)

and the *Royal Academy of Engineering* (RAEng) [28], found that suitable controls were available to mitigate the risks of undesirable seismic activity. It was argued that the most likely cause of the Preese Hall tremors was ‘induced seismicity’; caused by the injection of fracking fluid into and along faults that had already been under stress. The fault then shifts, leading to perceived surface tremors. The DECC subsequently announced the introduction of a set of requirements for new controls, permissions and risk assessments on fracking operations in 2012, including oversight by the *Health and Safety Executive* (HSE), at Preese Hall and all future shale gas exploration wells. They included a ‘traffic light’ seismic monitoring system [23], as advocated in the RS/RAEng study [28] and subsequently suggested by DECC: *Green* = $0.0 M_L$; *Amber* $0.0 \leq M_L \leq 0.5$; and *Red* $> 0.5 M_L$ [29]. Nevertheless, earth scientists (see, for example, Davies *et al.* [30]) viewed the RS/RAEng fault diagnosis as incomplete, and proposed the additional use of borehole imaging before injection. Recently Westaway and Younger [31] suggested that the existing regulatory limits applicable to quarry blasting could be readily applied to cover such induced seismicity. They argued that future fracking activities in the UK is only likely to cause “minor damage”, and that seismic monitoring could be used to ‘police’ compliance with the regulatory framework. The commercially-sponsored UK *Task Force on Shale Gas* (TFSG) in their second report [32] argued that the DECC ‘traffic light’ limits as possibly being “unfeasibly low”. However, they recommended that independent baseline monitoring should be carried out as early as possible, following the identification of a site to assess seismic risk going forward and also to increase public confidence.

Induced seismic activity has also been linked to the re-injection of large quantities of waste fluid post-fracking, rather than just in the initial hydraulic fracturing process itself [33], which has led to earthquakes of over $5 M_L$ on the *Richter scale* in the US. A recent study has linked such induced seismicity to disposal wells up to 35 km away [34], much further than previously considered. This practice is unlikely to be carried out in the UK reducing the risk of induced seismicity compared to the USA [29]. It is understood [31] that the reconstituted *Environment Agency* (EA) in England would not grant a permit for this method of wastewater disposal under its current interpretation of the European Union (EU) *Water Framework Directive*. However, the *Task Force on Shale Gas*, again in their second report [32], suggested that there “may be situations and circumstances - where the geology is suitable - where deep injection is sensible, cost effective and popular preferred means of waste disposal”. That assertion must be read with an understanding of the commercial interests of the sponsors of the TFSG. In any event, adequate alternative wastewater management systems would need to put in place to safely dispose or reuse of the resultant wastewater [35] away from the fracking site itself.

5. WATER USE AND CONTAMINATION

Fracking for shale gas typically takes place at depths many hundreds of metres (or several kilometres) below drinking water aquifers, although such wells and aquifers do not co-occur

everywhere. Unconventional gas enthusiasts argue that there have been no cases of groundwater contamination due to fracking in the United States, but the US *Environment Protection Agency* is less confident of that and its studies are therefore continuing. Hydraulic fracturing requires large quantities of water dependent on the properties of the shale rock involved. It ranges from 10,000-30,000 m³ of water per fracking operation or well [36,37]. There has consequently been a lot of publicity in the UK about the large amounts of water used during the fracking process. The primary water demand is for the initial hydraulic fracking process and each subsequent fracturing step, suggesting periods of high water demand, which could put temporal stresses on water resources locally [28]. Excessive water use may lead to a fall in the availability of public water supply, ecosystem degradation and adverse effects on aquatic habitats, erosion, and changes in water temperature [36]. But in the UK abstracting water will require a license from the *Environment Agency* (EA) in England [or the equivalent bodies in the other nations of the UK, i.e., *Natural Resources Wales* (NRW) and the *Scottish Environment Protection Agency* (SEPA)]. The abstraction of water resources under stress should therefore be avoided via this licensing process. Some of this water may be recyclable, although it could be contaminated, for example, by *Naturally Occurring Radioactive Material* (NORM). The RS/RAEng report [28] suggests that the latter are found in shales at significantly lower levels than safe exposure limits. However, NORMs only give rise to potential hazard if concentrated in scales, for example, which may be precipitated on pipework. In reality, sea water exhibits higher NORM concentrations than deep saline ground waters in the UK. Nevertheless, wastewaters require careful management and monitoring in order to ensure that NORMs do not become concentrated [36].

In the USA some concern has been expressed over the possibility of methane levels in water that might be high enough to be flammable [38]. It has been asserted by DECC [38] that these are normally caused by failures in the well construction or natural background levels of methane rather than fracking *per se*. Indeed the RS/RAEng review [28] considered the possibility of direct groundwater contamination to be very unlikely, although it could result from faulty wells. The RS/RAEng review also warned that environmental contamination, including 'faulty wells, and leaks and spills associated with surface operations', were to be expected as they are common to all oil and gas wells and extractive activities. They argued for integrated operational practices [28], such as recycling and reusing wastewaters, to ensure benign water handling and treatment. DECC [38] have put in place a series of requirements to minimise the risk of groundwater contamination from poorly fabricated wells. These include the need for detailed plans to be submitted to the regulator (the EA in England, NRW in Wales or SEPA in Scotland), together with formal risk assessments [35].

US experience suggests that around 40 – 80% of the injected fracking fluids will be returned to the surface as 'flowback water' [35,39]. This contaminated 'produced water' also poses a potential risk to groundwater once it reaches the surface [37,38]. In the event of human error or

equipment failure, it could potentially leak into streams and seep down to the groundwater. However, all drilling pads are double-lined with impermeable membranes and drainage is intercepted. Operators are required to dispose of flowback fluid from wells in a safe manner. Unlike in the USA, this wastewater is not permitted to be stored in open stores or disposed of by borehole injection [28], reducing the risk of this type of environmental instance in the UK. In addition, all fluids on site must be stored in double-skinned (or integrally ‘bunded’) tanks in case of spills. Similar hazards arise in other industrial processes, and those associated with hydraulic fracturing should be managed appropriately [10,28,40]. Thus, such risks may be ‘designed-out’ of the system. Fracking chemicals have to be assessed by the relevant regulator on a case-by-case basis.

6. ENVIRONMENTAL IMPACTS

6.1 Local Environmental Pollution, Health and Related Impacts

There are various local environmental impacts from shale gas fracking: the excessive water use, groundwater contamination and wastewater handling as discussed above, as well as noise, odours, and the disposal of solid wastes. In order to prevent contamination, the integrity of fracking wells must be ensured. Guidelines for achieving this were recommended in the RS/RAEng report [28], which are largely reflected in documents produced by the *American Petroleum Institute* and the HSE that are recommended by DECC [41]. It is believed that properly designed wells should not pose a risk of contamination to underground aquifers [41]. Of course regulation, however good, is ineffective without rigorous enforcement backed by seriously deterrent penalties. Both well design and construction are overseen by an *Independent Well Examiner* and the HSE Wells Inspector. No operation can commence before an inspection by the independent examiner (employed by the operating company or a contractor) who oversees the design, construction and maintenance of a well [42]. However fully independent monitoring of the wells which was recommended by the RS/RAEng report was rejected during the enactment of the UK *Infrastructure Act 2015* [43], primarily leaving the reporting of leakages up to the operating company. Furthermore, the monitoring or management of abandoned wells remains unclear, particularly if an operator becomes insolvent [42].

The (Smith) *Task Force on Shale Gas*, in their second report dealing with local environmental impacts [31], advocated that baseline monitoring of air, land and water should begin as soon as a potential shale gas fracking site had been identified, rather than waiting for planning permission to drill boreholes is granted. They also recommended that the adoption of the recently mandated US process of ‘green completions’ or ‘reduced emissions completions’, whereby the shale gas and associated hydrocarbons is separated from the remaining ‘flowback fluid’ and the rest of the fluid to be transferred on for further processing, as a compulsory framework for exploratory sites in the UK [31]. This process reduces is claimed to reduce ‘fugitive emissions’ by around 90%.

The TFSG recognised that *green completions* may not be feasible for exploratory wells in Britain, and that some flaring might be required. In that event, operators could convert gas to electricity onsite and link it to the grid as an alternative, more acceptable, option [31].

There are, in addition, aesthetic concerns: visual intrusion of the sort that also results from onshore wind turbine developments. Shale gas fracking requires site operations at the wellhead, as well as the collection and distribution of unconventional gas from the site [44]. Public resistance often focuses on the increased traffic and vehicle exhaust emissions and noise, particularly those emanating from heavy road transport vehicles. Indeed, the first planning application to explore shale gas in the UK was rejected by *Lancashire councillors* [the local authority in that part of the north west of England (see again Fig. 2)] on the grounds of increased noise and visual impact [44]. Drilling often takes place on landscapes of natural beauty that include sensitive wildlife habitats [45]. The *Infrastructure Act 2015* [43] prohibits hydraulic fracturing from taking place in land at a depth of less than 1000 metres, whilst ensuring that communities benefit and that the UK has a robust regulatory regime. The UK government had originally “agreed an outright ban on fracking in national parks, sites of special scientific interest (SSI) and areas of outstanding natural beauty” [45], but have subsequently made changes to these exclusion zones arguing that it could hamper this nascent industry. Surface-level fracking operations are prohibited in environmentally-sensitive areas, such as *National Parks*, *Areas of Outstanding National Beauty* (AONB), the Norfolk Broads, World Heritage Sites, and those where groundwater supplies may be at risk [46]. Sites of *Special Scientific Interest* (SSI) will no longer be excluded from the exploration of shale gas under these new terms. These changes were met by significant concern from environmental groups over the risk posed to some of the UK’s most important wildlife sites. Operational environmental permits for shale gas fracking in the UK are issued by the EA, NRW, or the SEPA (as appropriate) on a site-by-site basis in line with the requirements imposed in water abstraction licenses, and actual usage monitored over time.

6.2 Climate Change and Fugitive Emissions

The 2008 UK *Climate Change Act* [17] set a legally binding target of reducing the nation’s GHG emissions overall by 80% by 2050 in comparison to a 1990 baseline. In order to meet this reduction target, the Government’s independent *Committee on Climate Change* has suggested that the electricity generation sector will effectively need to be decarbonised by 2030. Gas-fired power stations emit far fewer greenhouse gases per unit of electricity output than coal-fired ones and, for this reason, it is favoured by Helm [47] as a transitional energy option. However, if the UK continues to build and operate gas-fired power stations, the power sector will be locked-in to a fossil fuel technology and unable to decarbonise over the lifetime of these gas-fired power plants unless paired with carbon capture facilities. Unfortunately, the UK Government recently cancelled (on 25 November 2015) their £1bn CCS competition, which suggests that this technology may have an uncertain future in Britain. A CCS option would add extra cost to power

generation and also constitute a significant risk of climate change policy failure. Many scientists, policy makers and journalists attributed the 7% reduction in US domestic carbon emissions between 2007 and 2013 to the fuel switch from coal to shale gas. But recent analysis suggested that it in fact only played a small role in this fall, with much of the reduction attributed to the economic recession [48].

Two of the main sources of global warming impact arising from shale gas development are the fugitive methane emissions leaked and vented during extraction processes, and carbon dioxide (CO₂) emissions from the combustion of the shale gas to produce electricity. Like conventional gas, the primary cause of these GHG emissions result from the combustion of the shale gas in boilers. However, there is a greater variation in fugitive methane emissions from the extraction process, depending on the given location, particularly in terms of enforced environmental legislation. Therefore, much of the controversy over the global warming impact of shale gas technology focuses on such fugitive methane. Methane is a much more powerful GHG than CO₂, although it resides in the atmosphere for only 12 years [49]. Some of it may be flared (converting it to CO₂), rather than vented, but this is not or cannot always be done.

The most recent values of *Global Warming Potential* (GWP) for GHGs are provided by the *Intergovernmental Panel on Climate Change* (IPCC) in their *Fifth Assessment Report* (AR5) over three separate time horizons [50]: 20, 100 and 500 year respectively. The application of the three different time horizons are all equally valid for assessing GHGs from a scientific perspective. However, short-lived, more potent GHG emissions have a much higher GWP over the 20 year horizon; consequently methane traps 86 times more heat than carbon over this period, compared to 34 over a 100 year horizon [50]. Some have argued that it might be more pertinent to consider methane emissions over the 20 year horizon to assess the danger it poses to our climate system in the short-term. Nevertheless, the 100 year horizon has been widely used by many, providing a balance between short-term and long-term impact of GHGs on climate change. Furthermore, this is particularly appropriate given that CO₂ accumulates over time in the atmosphere, whereas methane dissipates. Accordingly, the results presented in this assessment of the life-cycle GHG emissions from shale gas are over a 100 year time horizon.

Upstream GHG emissions estimated by several studies have been collated [51-57] in order to explore the potential ‘carbon footprint’ of UK shale gas (see Fig. 3). The controversial study by Howarth *et al.* [53] was excluded when averaging this data, because of its relatively high estimates for fugitive emissions. Should rigorous and effective environmental legislation be introduced in the UK, this level of emissions is unlikely to be permitted. Emissions data from the *Ecoinvent* database version 2.2 [58] were used to account for UK NG when generating the latter mix; for both domestic and imported UK fuel routes [from Norway, the Netherlands, the rest of the European Union (EU), and via LNG].

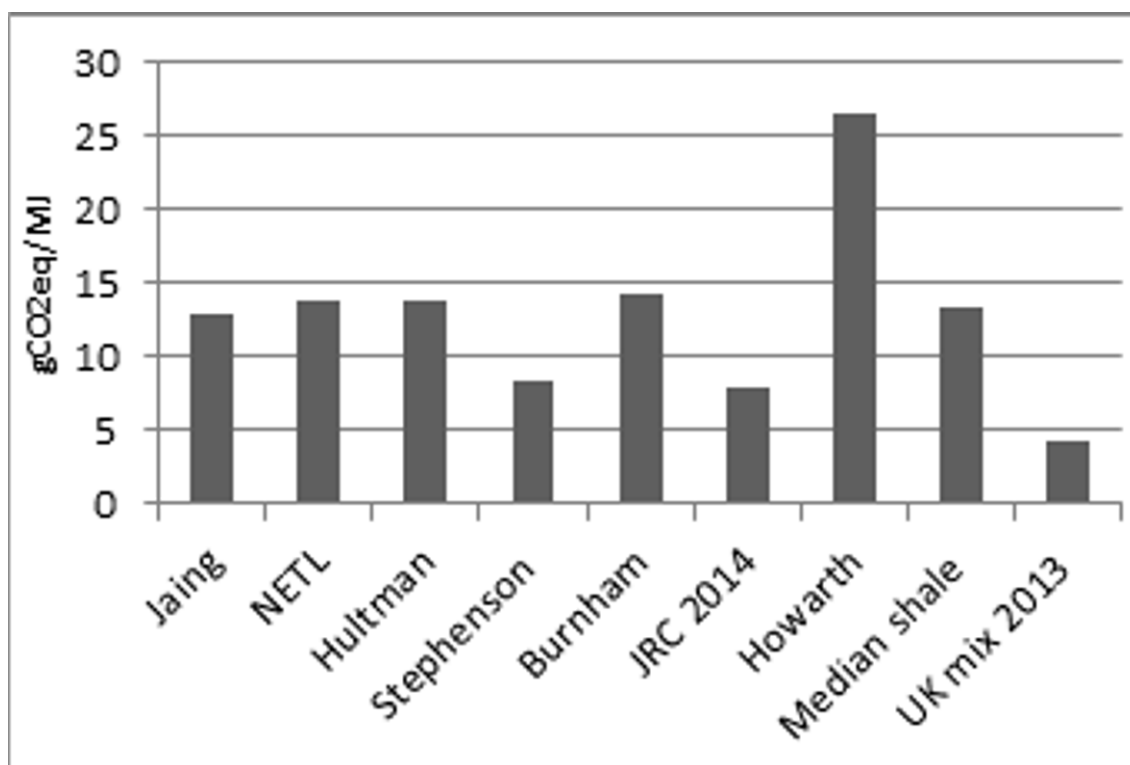


Fig. 3. Central estimates for upstream GHG emissions associated with unconventional gas compared to current UK gas mix

The full life-cycle GHG emissions of shale gas electricity generation are compared to the NG generation using the current UK gas mix, LNG and Russian gas respectively in Fig. 4. The LNG emissions data were taken from a review undertaken previously by Hammond and O’Grady [59]. The operational (or ‘stack’) emissions are based on current UK technology, but may fall over time as more efficient plants come online. Total life-cycle emissions of shale gas generation were estimated to be in the range of 480-546 gCO_{2e}/kWh_e, i.e., 4-18% greater than emissions from the current UK gas mix (with a central estimate of 14% greater GHG emissions). Thus, providing effective regulation to curtail fugitive emissions are in place, electricity generation using shale gas could offer significant savings in carbon emissions when displacing coal-fired generation as part of a transitional energy strategy [59]. This result is in keeping with other estimates found in literature [51,54] and a study carried out by DECC [60], which saw a moderate disparity between conventional and unconventional gas. There are large uncertainties associated with these findings, and they should only be considered as ‘indicative’ until real operational data are available.

GHG emissions from shale gas are currently higher than that associated with the UK gas mix, although shale gas may offer less GWP than its counterparts as the UK gas supply mix evolves over time, according to Hammond and O’Grady [59]. Over the coming years, both indigenous and European gas supply will decline, leaving the UK more reliant on imports such as LNG and Russian pipeline gas.

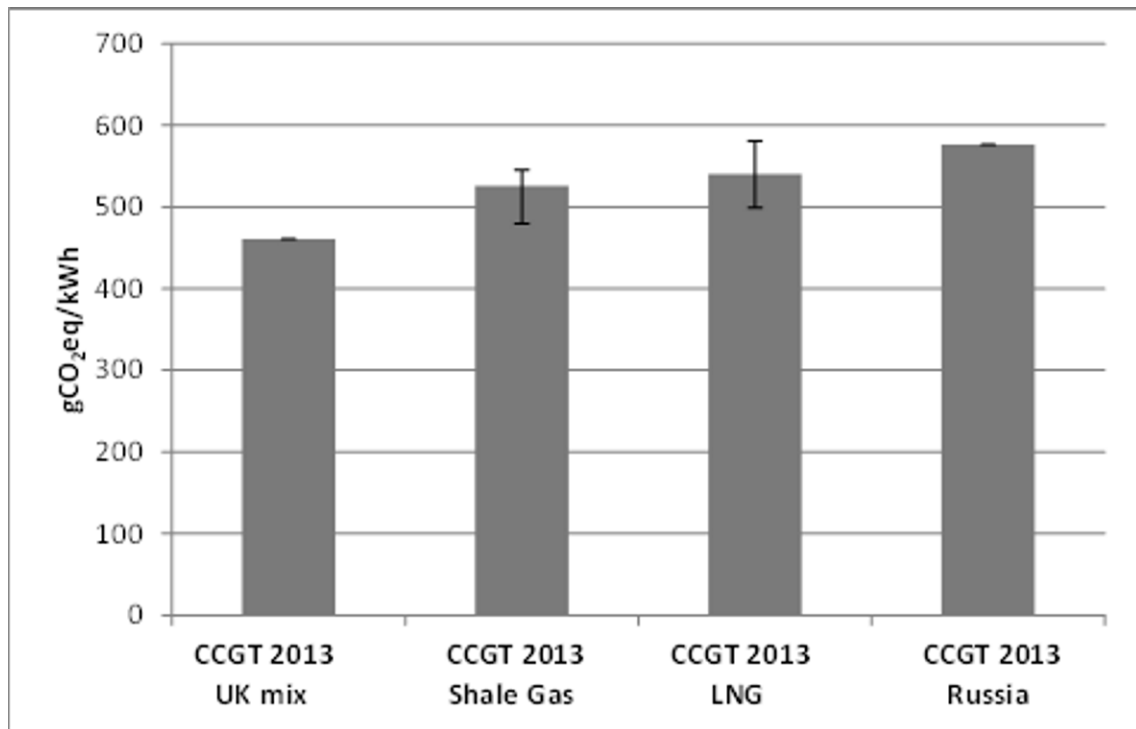


Fig. 4. Life-cycle GHG emissions for gas generation with different gas sources

LNG was found [59] to be 8-26% greater in terms of GHG emissions than the current UK gas mix, while Russian gas was seen to produce 25% higher emissions. These gas supplies from distant regions require long transportation routes through pipelines, which results in high fugitive emissions [61], or they must undergo liquefaction, shipping and regasification: all energy intensive processes that result in additional GHGs being emitted. The development of a UK shale gas industry could decrease the share of these impactful gases in the future UK gas mix, but are likely to impede the penetration of biomethane, which could still result in increased emissions [59]. Similarly, the growth in UK shale gas may provide a cheap supply of gas that could greatly reduce the investment in renewables, and devalue efforts to adhere to carbon budgets.

Sensitivity analysis performed in connection with shale gas studies have shown large ranges in the impact of shale gas, particularly in terms of fugitive emissions and the estimated ultimate recovery per well [62-65]. Hence, without effective regulation (backed by rigorous enforcement and seriously deterrent penalties) to minimise these fugitive methane emission, many of the notional advantages of shale gas may not be realised. An interesting study in the specific context of the Central Belt of Scotland [65] found that significantly greater methane emissions are likely to arise from shale gas extraction on peatland, in contrast to grassland development typical of the English landscape. However, comparisons between the full chain GHG emissions from conventional and shale gas were taken from the DECC study [60] mentioned above. Legislation to address fugitive methane from shale gas have not yet been specified in the UK, however, it is likely that they will be treated in the same manner as fugitive methane from current UK oil and gas production. Consent for venting or flaring in this sector (reserved mainly for maintenance and emergency procedures) must be granted by DECC [66], who are committed to keeping these

emissions to a technical and economic minimum. It would be desirable for such ‘green completion’ techniques, which were also advocated in the second report of the (Smith) *Task Force on Shale Gas* [31], to be mandated during both the explorative and operational phases of the well in order to keep fugitive emissions at an absolute minimum.

The third report of the *Task Force on Shale Gas* (TFSG), published in mid-September 2015, dealt with the climate change impact of shale gas development in the UK [67]. It suggested again that that this would be similar to that for conventional gas, provided that the British shale gas sector is “properly regulated” and monitored, and lower than those associated with LNG. They advocated technological innovation and RD&D investment in CCS alongside the extraction of shale gas as a climate change mitigation option. This, they believe, would enable gas to play a transition role in the UK energy mix in the medium-term as advocated by Helm [47] and others [59]. Nevertheless, the TFSG argued that the sector should not prohibit the development of low-carbon energy generation (particularly from renewables), storage and distribution [67]. Just a little after the date that the third report of the TFSG was launched, so too was a review of GHG emissions from conventional and unconventional sources of natural gas over their respective full supply chains [68] by the *Sustainable Gas Institute* (SGI; based at Imperial College London with industrial funding from *BG Group*). These sources included conventional onshore and offshore, shale gas, tight sands, and coal bed methane (CBM). It drew on findings from some 400 papers in order to evaluate the emissions emanating from various extraction, processing and transport routes; albeit mainly based on data from North America. Comparisons were collated between the full chain GHG emissions from conventional and unconventional gas. It found that over the complete range of gas supplies the total GHG emissions associated with electricity generation was 419–636 gCO_{2e}/kWh_e (with a central estimate of 496 gCO_{2e}/kWh_e), which the SGI considered to be well below typical GHG estimates for coal-fired power plants of around 1,000 gCO_{2e}/kWh_e. These embrace the range of full chain emissions found from the present study above, although they are obviously much broader than shale gas data. Unfortunately, the SGI figures were not disaggregated in terms of fuel type (e.g., conventional versus shale gas for the current purposes).

6.3 Comparing Environmental Burdens from Different Life-cycle Impact Categories

Climate change is the primary focus of most of these studies of shale gas, with little attention given to its wider environmental implications. The first life-cycle assessment was only recently conducted by Stamford and Azapagic [64] but has generated some controversy in the way their results have been represented in the media: as, for example, “fracking trumps renewables” [according to a Media Release by the UK *Institution of Chemical Engineers* in their members’ magazine (‘The Chemical Engineer’).< <http://aboutdatajournalism.org/tcetoday-news-lca-shows-fracking-trumps-renewables/>>]. This is because the authors examined a variety of life-cycle impact categories in addition to climate change (for which their central estimate was 462

gCO_{2e}/kWh_e) with varying results between other environmental burdens. Shale gas was comparable or superior to conventional gas, nuclear power and renewables in terms of the depletion of abiotic resources and eutrophication, as well as freshwater, marine and human toxicities. In contrast, they found shale gas to be more environmentally damaging when photochemical smog and terrestrial toxicity were examined; both, of course, are associated with excess human mortality. Nevertheless, carbon footprints have become the ‘currency’ of debate in a climate-constrained world [59], where the UK is seeking to dramatically reduce its carbon emissions by 2050. It is therefore of greater significance than these other (important, although perhaps not critical) impact categories. In that regard, shale gas fracking certainly does not “trump renewables”.

Stamford and Azapagic’s study [64] has attracted other criticisms, including that by Westaway *et al.* [69]. The latter expressed doubt over some assumptions taken in a UK context in regards to drilling waste disposal, well completion, and the *Estimated Ultimate Recovery* (EUR) of the wells. Westaway *et al.* argued that Stamford and Azapagic assumed that practices that carried out in the USA, that have long been illegal in the UK (and EU generally), would potentially be used by the shale gas industry in Britain. However, Stamford and Azapagic stressed that the large uncertainties involved in their work was due to the nascent nature of the British shale gas industry. Despite the criticisms, their study [64] demonstrates the high sensitivity of the LCA results to particular parameters of shale gas, reporting large ranges in life-cycle impacts for UK shale gas. It is critical that robust environmental data is collected as an industry grows in Britain, with strong collaboration between operators and the EA.

In view of the early stage of UK shale gas development and of the consequent scarcity of country-specific data, baseline monitoring studies are being planned and undertaken in order to provide GHG emissions and related data over the British supply chain employing airborne, remote sensing, sampling, and sensor network methods. Thus, Allen *et al.* [70] have obtained and validated trace-gas-concentration and thermodynamic profiles throughout the troposphere and planetary boundary layer using data from aircraft campaigns over and around London. Similarly, Sommariva *et al.* [71] have taken shale samples from the Bowland-Hodder formation (in northern England) in order to determine, using mass spectrometry, methane and non-methane hydrocarbons (NMHCs). Their results indicate that high temperatures significantly increase the amount of NMHCs released from shale, whilst humidity tends to suppress them. A large fraction of the gas is also released within the first hour after the shale has been fractured. Clearly, much more needs to be done in terms of such basic data gathering for real-world hydraulic fracturing operations in the UK. Such data would help reduce uncertainty and allow the potential environmental impact of UK shale gas to be more accurately determined.

7. PUBLIC AND STAKEHOLDER ENGAGEMENT

UK Government Ministers have indicated their concern over the fierce resistance to their shale gas fracking policies; particularly from rural communities in both the south and north of England. Potential sites stretch all the way from Dorset to the Kent borders (across the south), via the Bowland-Hodder (in northern England), to at least the Midland Valley of Scotland (see again Fig. 2). There are also potential shale gas reserves in Wales, although there is a relative paucity of data for the Principality. Initial concerns were raised in northern England as a result of induced seismicity caused by exploratory drilling at Preese Hall. Such communities need to be engaged in a two-way dialogue aimed at clarifying the impacts of the shale gas fracking process, along with its potential costs and benefits. Challenges to energy infrastructural developments in the form of local activism have typically been led by groups, such as the Green Parties (of the nations of the UK) and environmental campaigning organisations, like *Friends of the Earth* and *Greenpeace*, as well as various nature conservation bodies. Public opposition could prove to be a ‘showstopper’ for this energy option unless the various stakeholders are engaged in an appropriate consultation. Pigdeon *et al.* [72] recently examined some of the critical issues concerning the design and conduct of public deliberation processes on energy policy matters of national importance. In order to develop their argument, they employed as an illustrative case study, some of their earlier work on public values and attitudes toward future UK energy system change. They note that national-level policy issues are often inherently complex; involving multiple interconnected elements and frames, analysis over extended scales, and different (often high) levels of uncertainty. It is their view that facilitators should engage the public in terms of ‘whole systems’ thinking at the problem scale, provide balanced information and policy framings, and use different approaches that encourage participants to reflect and deliberate on the issues. This is similar to what is often referred to as interactive, participatory methods by the technology assessment community [3-5].

DECC has engaged in a process of evaluation of public attitudes to various energy technologies [73], including shale gas fracking. They have commissioned periodic surveys of just over 2000 face-to-face in-home interviews with adults over 16 years of age by specialists from the *Office of National Statistics* (ONS) in a series, or wave, of studies. The most recent (August 2015) survey [73] indicated that around $\frac{3}{4}$ of the British public were aware of fracking, although only 14% indicated that they knew a significant amount about the process. Of the sample, some 46% were neither supporters nor opponents of extracting shale gas. Those that offered an opinion indicated that around 28% were opposed, whereas 21% supported of the exploitation of this technology. DECC have suggested, on the basis of the ONS survey, that support for fracking is related to awareness with 54% of those who claim a lot of knowledge being opposed to the technology (in contrast to 32% in favour of shale gas fracking) [73].

An academic study of UK public perceptions of shale gas fracking by O'Hara *et al.* [74] has attracted a lot of attention amongst social scientists and policy makers in Britain [37]. It included analysis of policy documents and media sources, semi-structured interviews, and a series of seven nation-wide surveys over the period 2012-2013. The initial survey indicated that 37% of respondents were familiar with shale gas extraction, but this rose to over 60% and then flattened out. This latter phenomenon occurred in spite of a significant increase in media coverage of fracking over this period, particularly via the BBC. O'Hara *et al.* [74] found that respondents under 25 years of age were least aware of shale gas extraction and its implications. Over 58% of people thought that it would aid energy security, although respondents answered 'don't know' to questions about how shale gas development would impact in terms of climate change. The majority of people who were familiar with the process felt that it should be permitted. Another recent, detailed experimental (online) survey of public perceptions of shale gas fracking in the UK (N = 1457) by Whitmarsh *et al.* [75], included analysis of the effects of different messages on support for, or risk perceptions of, shale gas fracking. They found that the public were generally ambivalent about shale gas, but perceived more risks than benefits. This was strongly influenced by demographic, political and environmental considerations and values. The study [75] discovered that prior knowledge of shale gas extraction had the greatest impact on those respondents who were initially ambivalent or 'undecided', which suggested an important role for information and awareness raising.

The (Smith) *Task Force on Shale Gas* also considered matters around local engagement in their first report [76]. They proposed the establishment of a community engagement plan by operators (albeit with local community involvement) and the full disclosure of information to the local community before an application is submitted to the appropriate regulator. The latter should include logistic and broad site access issues [76], such as the likely number and size of transport movements over the life of a potential drill pad. The *British Geological Survey* has been involved in practical activities associated with public engagement about shale gas fracking [Dr Robert Ward, BGS, UK, private communication 06.11.15]. They have advocated interaction much in line with that recommended by TFSG [76] although, in addition, the BGS stress the need to utilise tailor-made approaches for different areas/groups, as well as the importance of keeping "information up-to-date, fresh and understandable". Further elaboration of such surveys, employing the deliberative framework proposed by Pigdeon *et al.* [72], might go some way towards securing better awareness and understanding of hydraulic fracturing by the public in general.

8. PLANNING, REGULATION AND MONITORING

One set of issues for which politicians of different persuasions and community groups agree on is the important need for adequate measures in the area of unconventional gas planning and regulation. Nevertheless, it has yet to be determined whether what community groups consider

effective regulation will be accepted and upheld by the government. For instance, many local groups are opposed to recent moves by the UK Government to facilitate planning permission for fracking by preventing landowners objecting to the process taking place under their land [77]. DECC issues licenses to onshore oil and gas operators for exclusive drilling rights, and have listed a long set of pre-drilling approvals that are needed from the various regulators [1]. Operators are required to obtain planning permission from the appropriate UK minerals planning authority (county council or unitary authorities in England and the planning authorities in Scotland and Wales) and seek access to the site from landowners [1].

The *Environment Agency* (EA) in England is currently undergoing a consultation to define new standard permits for onshore oil and gas [78]. The process of applying for permits to drill and carry out preliminary testing of wells would be streamlined by removing public consultation. Although a separate permit for hydraulic fracturing will still be required, this has been seen by many as a move to simplify the process and reduce costs for operators. It has also been argued that prior independent [28,31] evaluations of well integrity should be undertaken before drilling can commence, followed by mandated disclosure of hazardous incidents, ongoing process monitoring and contamination assessments. *Public Health England* (PHE) [79], for example, have recently proposed that baseline environmental monitoring be instigated in order to facilitate the impact assessment of shale gas extraction on the environment and public health, that the fracking chemicals (including NORMs) should be publicly disclosed and their risks assessed before use, and that the type and composition of the extracted gas should be determined on a site-by-site basis. This was criticised by a group of medical specialists from the US [80], who argued that it was based on the idea that many of the public health problems experienced in the USA would be replicated in a more densely populated country like Britain. Law *et al.* [80] suggest that these impacts as yet remain undetermined and require further scientific study using rigorous, quantitative epidemiological methods. However, the UK *Task Force on Shale Gas* [31] generally agreed with the PHE recommendations, but also proposed that the Government should establish a ‘National Advisory Committee’ of independent academic experts to monitor data from shale gas operations in order to evaluate health impacts.

The TFSG also examined planning and regulatory issues in their first report [76]. Their main recommendation was that the UK Government should explore the possibility of creating a new, bespoke regulator for onshore underground energy (unconventional oil and gas, including CBM) that would take over the current regulatory responsibilities of the *Environment Agency* (and its national counterparts), the *Health & Safety Executive*, and DECC. The (Smith) Task Force also suggested [76] that full-scale ‘environmental impact assessments’, which they view as being not easily accessible, should be replaced by ‘environmental risk assessments’ [35]. The TFSG argued [76] that the latter methodology would be “more succinct and approachable” for use by the new regulator in a way that could be made readily available to local communities.

9. CONCLUDING REMARKS

An energy technology assessment (ETA) has been undertaken [3-5,13,14] in order to evaluate the credit and debit ‘columns’ of the shale gas fracking ‘balance sheet’. The adoption of this extraction technology is at a very early stage in the UK with great uncertainty over the scale of the potential shale gas resource. An extensive programme of investigative drilling across the country will therefore be needed in order to provide reliable estimates; possibly requiring hundreds of exploratory wells [20,21]. Nevertheless, the successful exploitation of large-scale development of shale gas extraction in the UK might contribute positively in terms of fuel security and independence, as well as jobs and growth, providing the potentially harmful ‘side-effects’ outlined here can be satisfactorily resolved. But it is unclear whether job creation would be any greater than that arising from equivalent programmes aimed at supporting the adoption of energy demand reduction measures or small-scale low carbon energy options. Similarly, the UK balance of payments would benefit, although it is unlikely that gas bills for household and industrial consumers would fall dramatically as they have done in North America. This is because the UK is part of the wider European natural gas market [23,37] where the gas price is determined by the supply and demand for indigenous natural gas, imports from Russia, and LNG from North Africa. Unconventional gas supplies in the UK will be only be a small fraction of those in this wider market. Lessons from the present ETA study will therefore also apply in general across the European Union, albeit tailored by local circumstances.

Hydraulic fracturing requires significant quantities of water which may potentially lead to a fall in the availability of public water supply, ecosystem degradation and adverse effects on aquatic habitats, erosion, and changes in water temperature [28]. However, abstracting water in the UK will require a license from the *Environment Agency* (EA) in England [or the equivalent bodies in the other nations of the UK, i.e., NRW and SEPA]. The abstraction of water resources under stress should therefore be avoided via this licensing process. Recycled fracking fluid could be used for ongoing fracking operations [35,36], except that a proportion of this is not recovered. In the USA some concern has been expressed over the possibility of methane levels in water that might be high enough to be flammable. It has been asserted by DECC [38] that the high methane levels found in some US drinking water supplies were caused by failures in the well construction or natural background levels of methane, rather than fracking *per se*. They have put in place minimum requirements to avoid groundwater contamination from poorly fabricated wells. Fracking chemicals have to be assessed by the appropriate regulator (EA, NRW or SEPA) on a case-by-case basis [79]. Operators are required to dispose of ‘flowback fluid’ from well in a safe manner.

The life-cycle carbon footprint of shale gas has been shown to be lower than that of coal-fired power generators providing stringent regulation is implemented to minimise fugitive methane emissions. On the other hand, the life-cycle carbon footprint was found to be slightly higher than

conventional gas, and considerably higher than nuclear power and renewables. It could therefore form part of a transitional UK energy strategy [47,59], although this might jeopardise the attainment of a low (near zero) carbon transition pathway by 2050. The penetration of shale gas into the UK energy mix would likely lead to the lock-in of gas-fired power generation for some decades. Furthermore, without the large-scale use of *carbon capture and storage* (CCS) [81], such a transition would be incompatible with meeting legislated carbon budgets and limiting GHG concentrations to a 'safe' level [82].

The socio-economic benefits and costs of shale gas fracking are not evenly distributed between various communities and demographic groups. Thus, the UK overall might benefit from improved energy security and reduced balance of payments, whilst it will be local communities that bear any adverse environmental and health risks of fracking. Induced seismicity caused by the injection of fracking fluid into and along faults that are already under stress can lead to minor earthquakes or surface tremors. DECC have introduced a set of requirements for new controls, permissions and risk assessments on fracking operations in 2012, based on a 'traffic light' system [27-29] to monitor unusual seismic activity. However, several prominent UK earth scientists have argued [30,31] that future fracking activities in the UK are only likely to cause 'minor damage'; yet again, provided a robust regulatory framework is put in place. Local environmental impacts are critical to neighbouring communities near the wellhead. They focus on shale fracking site operations, as well as the collection and distribution of unconventional gas from the wellhead [44,47]. Public resistance has been largely concerned about increased traffic, which causes vehicle exhaust emissions and noise [79], particularly those emanating from heavy road transport vehicles. In addition, drilling places environmental burdens on landscapes that are often in areas of natural beauty with sensitive wildlife habitats [47].

In order to draw up an objective and rigorous 'balance sheet' for the fracking of shale gas (or indeed other critical technologies) as part of a national dialogue, it would be desirable to bring together experts from a range of disciplines in order to carry out the necessary ETAs. They would need to interact with national and local stakeholders: 'actors' both large and small. That work should be seen by the wider community as *analysis* and not *advocacy*. The UK Coalition Government, when it came into office in 2010, unfortunately closed down or withdrew funding from a number of independent, 'arms-length' bodies established by government departments (sometimes known by the term 'quasi-autonomous non-governmental organisations', or 'Quangos') who might have been capable of conducting studies of this type. Two such bodies were the *Royal Commission on Environmental Pollution* and the *Sustainable Development Commission*. It is unlikely that the present government would re-establish these organisations, but perhaps a future government might consider establishing an alternative. One model might be the *Office of Technology Assessment at the German Bundestag* (TAB), or the equivalent bodies in the Scandinavian countries [4]. In the present context, a new UK agency might look wider than

just the scientific and engineering issues, bringing together the technical with the social science perspectives. The latter would be critically important in obtaining insights from various stakeholder groups. That would guard against unwanted side-effects by identifying them in advance of deployment, and could go some way towards engaging and reassuring the community. Constraints on the exploration for unconventional gas are likely to be as much about public acceptance as they are about the various technical issues [72-76]. Community engagement in a genuinely participative process will consequently be critically important for the adoption of any new energy option [3,4] that might meet the needs of a low carbon future. That is certainly one lesson from the shale gas fracking controversy.

ACKNOWLEDGEMENTS

This is an extended and updated version of a paper originally presented at the 7th *International Conference on Applied Energy* (ICAE2015) held in Abu Dhabi, UAE over the period 28-31 March 2015 (denoted then as paper ICAE2015-600). The work reported forms part of a programme of research at the University of Bath on the technology assessment of low carbon energy systems and transition pathways that is supported by a series of UK research grants and contracts awarded by various bodies. In the present context, the first author (GPH) is jointly leading a large consortium of university partners funded by the UK *Engineering and Physical Sciences Research Council* (EPSRC) entitled ‘Realising Transition Pathways: Whole Systems Analysis for a UK More Electric Low Carbon Energy Future’ [under Grant EP/K005316/1]. The second author (AO’G) is wholly funded as a Research Associate via this grant. Both authors are grateful for the interaction with other members of the Consortium (and its predecessor) made up of participants from nine UK universities.

Since the ICAE2015 conference version of this paper was delivered, the first author (GPH) participated in a specialist *Joint US-UK Workshop on Unconventional Hydrocarbons* held at Virginia Tech Research Center in Washington DC over 5-6 November 2015. Its technical programme was arranged by Prof. Richard Davies of Newcastle University (UK) and Prof. Danny Reible of Texas Tech University (USA). The British participants were supported by the UK *Natural Environment Research Council* (NERC) and those from the US by the *National Science Foundation* (NSF). Insights from this workshop, particularly in regard to the exploration for shale gas extraction in the UK, have been incorporated into the revised paper as appropriate. Both authors have also greatly benefitted from critical comments on an early version of this paper by their University of Bath colleague Dr David E. Packham (Emeritus Senior Lecturer in Materials Science). Finally, they are grateful to an anonymous reviewer (“an experienced well engineer”) for elaborating on some of the mining engineering and geological aspects of the paper. However, the views expressed here are those of the authors alone, and do not necessarily reflect the opinions of the collaborators or the policies of the funding body.

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8.6 Key Outputs

The advantages and disadvantages associated with shale gas production in the context of the UK energy future were examined in this paper, exploring the economic, environmental, safety and social repercussions of shale gas technology adoption. This paper meets objective five of this thesis, by examining the environmental impacts associated with shale gas extraction, and its role in the decarbonisation of the UK electricity sector.

Key environmental concerns were addressed in this paper, such as induced seismicity, water use and contamination, local pollution and related impacts, and impact on climate change. It was determined in this paper that many of these environmental issues could either be completely circumvented, or greatly reduced by sanctioning the following measures:

- Baseline monitoring of air, land and water, and independent monitoring of seismic activity before and during operation.
- Abstracting water in line with current UK licensing process.
- Careful management of wastewater.
- Properly design wells with guaranteed high well integrity.
- Disposal of flowback fluid in line with current regulation.
- Adoption of ‘green completions’.

The UK regulatory framework is far more stringent than in the USA, and is therefore likely to reduce the number of environmental incidents. Even with the most stringent regulatory system in place, issues such as faulty wells, leaks and spills are expected to occur, as they are common in all oil and gas well activities. Nevertheless, a regulatory system is only as strong as its enforcement, strengthened by tough deterrent penalties.

The shale gas revolution in the USA has been widely accredited for the significant GHG reduction across the economy over recent years. Detailed analysis investigating USA’s GHG emissions found that it, in fact, played a rather minor role, attributing most of the reduction to the concurrent economic recession. The life cycle GHG emissions associated with shale gas electricity generation was estimated to range between 480-546gCO₂/kWh when examined in this paper; 4-18% higher than emissions from gas generation consuming the current UK gas mix. It was therefore asserted that provided effective regulation to curtail fugitive emissions was enacted, shale gas could offer significant savings in GHG emissions when displacing coal as a part a transitional energy strategy. However, an over reliance on gas-fired generation could lead to high GHG emissions lock-in over the course of the gas plants life, associated GHG emissions were, on average, significantly lower than its LNG and Russian gas counterparts, suggesting it may be a less impactful gas source as domestic natural gas supply diminishes.

9 Article VI- ‘The life cycle greenhouse gas implications of a UK gas supply transformation on a future low carbon electricity sector’

9.1 Journal Paper

G. P. Hammond and Á. O'Grady, 2016. *‘The life cycle greenhouse gas implications of a UK gas supply transformation on a future low carbon electricity sector’*

Accepted for publication in Energy on 27th of October 2016

9.2 Contribution to Research:

This paper examines the potential transformation of the UK Natural Gas Supply as domestic production continues to decline out to 2050. In contrast to this decline, natural gas is set to remain a crucial source of energy, acting as a ‘bridging fuel’ to facilitate a transition from coal to low carbon energy sources. A switch to more unconventional gas sources such as shale gas and biomethane is expected, as is the import of natural gas from more distant regions in order to meet this continued demand. Prior to this work, the implications of a transformation of the UK gas supply on greenhouse gases have not been determined.

A consequential life cycle approach was taken in this paper to investigate the future dynamics of the gas market, and its impact on greenhouse gas emissions from the British electricity system. Current decarbonisation policies may lead to a shift in practices and adoption of production routes with unintended negative effects upstream, which are currently not adequately accounted for. Three potential gas supply mix scenarios were developed in this paper based on future trends in the gas markets in order to address these uncertainties which pose a significant risk to a low carbon future in the UK. This research addresses objective 5 and 6 of this thesis by assessing the environmental impact of large systemic change, and the introduction of new entrant generators, and their subsequent impact on the future UK electricity performance. Furthermore, this analysis contributes to the delivery of objectives 2 and 3 of this thesis, by quantifying the life cycle GHG emissions of the future UK power sector, and highlighting the significance of upstream emissions.

9.3 The Significance and Originality of the Article

This analysis represents the first assessment of the implications of an evolving gas supply on the GHG performance of the future UK electricity system. Critical findings were deduced, such as the need to ensure continued support for both biomethane and CCS (even at moderate contribution), otherwise the level of gas generation must be curtailed in response to rising total life cycle emissions. The insights derived from this research will help policy-makers tailor

9.4 Contribution by Candidate:
future energy and decarbonisation policies to limit the impact of rising gas supply GHG emissions. Main author (generating 95% of content)

The candidate developed the concept and design of this paper, and carried out all data analysis and acquisition of data. The candidate drafted the full manuscript, with critical revision and guidance provided by the other author. The final review of the paper was also conducted by the candidate.

The life cycle greenhouse gas implications of a UK gas supply transformation on a future low carbon electricity sector

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Keywords: Resources, Electricity Futures, Shale gas, Biogas, Gas supply, Low Carbon Futures

Abstract

Natural gas used for power generation will be increasingly sourced from more geographically diverse sites, and unconventional sources such as shale and biomethane, as natural gas reserves diminish. A consequential life cycle approach was employed in this paper to examine the implications of an evolving gas supply, and its effect on the greenhouse gas (GHG) performance of a future United Kingdom (UK) electricity system. Three gas supply mixes were developed based on supply trends, from present day to the year 2050. The contribution of upstream gas emissions - such as extraction, processing/refining, distribution and other associated activities - is not fully reported or covered by UK government legislation. However, upstream gas emissions were seen to be very influential on the future electricity systems analysed; accounting for 25-70% of overall GHG emissions for the electricity sector in 2050, compared to 3% for the current system. Increasing uptake of biomethane in the gas supply led to a substantial reduction in direct fossil emissions from combustion, which was found to be critical in offsetting the increases in upstream emissions. Accordingly, the modelled high shale gas scenario, with the lowest biomethane adoption; thus resulted in the highest GHG emissions on a life cycle basis. The long-term dynamics of upstream processes are explored in this work to help guide future decarbonisation policies, in order to avoid unforeseen negative cause and effect.

1 Introduction

Gas has been widely touted, by both academics and policymakers, as a critical bridging fuel in society's transition to a lower carbon future [1, 2]. Global organisations such as the *Intergovernmental Panel on Climate Change* (IPCC) and the *International Energy Agency* (IEA) see gas-fired generation as a vital bridging technology during this transition [3, 4]. Gas is defined here as a gaseous combustible mixture of hydrocarbons, consisting largely of methane (CH_4), which may also contain colliery methane, shale gas and biogas. Compared to other fossil fuels, 'gas' contains the lowest quantity of carbon per unit energy of any fuel, i.e. it has the most favorable C:H ratio, leading to much lower carbon dioxide emissions during combustion. Moreover, gas-fired generation is an inherently flexible conversion technology; ideal for providing backup to intermittent power generation [5]. Accordingly, both gas power generation with and without 'Carbon Capture and Storage' [6] have been proclaimed as key generation technologies in the UK's energy transition [2, 7]. Serious doubts have been raised over the future of CCS in the UK in the wake of the UK government scrapping a £1bn funding competition to help CCS reach full-scale development. Nonetheless, both the *Committee on Climate Change* and the *Energy Technologies Institute* have projected that failure to deploy CCS could double the cost of a low carbon transition [8, 9].

Bringing primary fuel to a gas power plant requires many upstream processes, including extraction, processing/refining, and transport, all of which expend energy and material resources and result in the release of greenhouse gas (GHG) emissions. Additionally, significant fugitive methane emissions often occur during production activities, and during the transport and handling of the gas. Upstream emissions are not exclusive to gas-fired generation, indeed, all electricity generators come with such associated emissions, from coal generation to solar photovoltaics, although they vary depending on the nature of that given system. Gas-fired generation offers significant GHG saving on an operational basis compared to coal, however, upstream emissions can vary greatly between gas source and geographical location [10]. Upstream processes will gain relative importance as the performance of combustion technologies improve over time and with increased penetration of CCS in the electricity sector. Consequently, it is hypothesized that the gas supply mix may have a considerable bearing on the cumulative emissions from the future UK electricity sector.

Since 2004, the UK has been a net importer of gas [11], relying increasingly on international gas markets. Gas will be increasingly sourced from more geographically diverse sites, and/or more unconventional sources, such as shale and biomethane. The reshaping of the gas supply, as explored in this paper, could lead to an increase in the life cycle emissions of gas-fired generation, which are not currently fully addressed by legislation. Presently, only domestic emissions are included in the national GHG inventory, neglecting all non-domestic upstream activities and associated emissions

which would be connected to any product chain [12]. Accordingly, upstream GHG emissions associated with the gas supply have not been well accounted for by the UK government. Previous analysis by both the independent *Committee of Climate Change* (CCC) and the then Chief Scientific Advisor to the *Department of Energy and Climate Change* (DECC) have regarded these upstream emissions as ‘fixed’, and ‘inconsequential’ in terms of their contribution to overall life cycle emissions associated with gas-fired generation [13, 14]. However, both DECC and CCC are wrong in this assertion given that UK gas upstream emissions are set to change over the coming years, in response to a large transformation of the gas supply, as domestic natural gas diminishes [15]. Furthermore, their contribution to the GHG performance of UK electricity will become increasingly significant, as upstream gas emissions rise and are contrasted against an increasingly decarbonised electricity sector.

Decarbonisation of the ‘Electricity Supply Industry’ (ESI) forms the cornerstone of the UK Government’s strategy to tackle climate change, as part of its transition towards a low carbon economy [2]. Current decarbonisation policies may lead to a shift in practices and adoption of production routes with unintended adverse effects upstream, which would not be accounted for under current UK carbon budgets [16]. The effect of an evolving gas supply on the future GHG performance of the ESI has not been fully explored to date, with only the implications of the shale gas penetration been previously considered by others in the field [17]. Wider trends in the gas market have been overlooked, such as the possible introduction of biomethane and shale gas, or in the long-term, the potentially infiltration of Russian gas. Indeed, in a letter to the House of Commons’ *Environmental Audit Committee*, the CCC highlighted the need to adequately capture the ‘life cycle emissions of shale gas and alternatives’ in future evaluations of the UK’s net carbon accounting [18]. In addition to addressing recognised gaps in knowledge [19], this work aims to inform policymakers of the potential implications a changing fuel supply, particularly the uptake from alternative sources such shale gas and biomethane out to 2050. Increased understanding of the intricacies and dynamics of future energy systems, will better frame future decarbonisation policies, avoiding unintended, adverse cause and effects. This work is founded upon earlier life cycle environmental appraisal of the UK ESI, it forms part of an ongoing research effort, evaluating and optimising the performance of various sustainable energy systems [16, 20-23].

A consortium was established to examine the role of electricity within the context of ‘Transition Pathways to a Low Carbon Economy’ across nine university partners. This multi-disciplinary team developed three socio-technical scenarios or ‘transition pathways’ towards a UK low carbon energy system as summarised in table 1 [24, 25]. Each pathway was characterised by different dominant governance ‘logics’: driven by the market, central government intervention, and local community

initiatives respectively. Previously, an environmental appraisal was performed for the ‘transition pathways’ of the UK ESI on a life cycle basis [16]. Upstream emissions were calculated assuming present day static fuel supply chains, a limitation when assessing a future system. In this present study, the ‘transition pathways’ have been paired with three future gas supply mix scenarios, which were developed to examine the uncertainties, and impact of dynamic upstream processes on decarbonisation strategies.

Table 1. Transition Pathways overview: adapted from Foxon [7]

	Market Rules (MR)	Central Co-ordination (CC)	Thousand flowers (TF)
Governance	Market logic	Government logic	Civil society logic
Key technologies	Coal and gas CCS; Nuclear power ; offshore wind	Nuclear power; Coal and gas CCS; offshore wind	PV; Onshore & Offshore Wind; renewable Combined heat & power
Key trends	Limited interference in market arrangements; high level policy targets and high carbon price	Central government commission tranches of low-carbon generation from big companies to reduce risk of low carbon investment	Local, bottom-up diverse solutions led by local communities & NGOs, greater community ownership and more engagement of end-user
Electricity Demand	Increase demand for heating and transport Overall demand in 2050 (512TWh) much greater than today	Increase demand for heating and transport, but reduced through energy efficiency. Overall demand in 2050 (410TWh) slightly higher than today	Overall demand in 2050 (310TWh) lower than today. Higher rate of energy efficiency improvements and more aware consumers.

2 Methods

2.1 Dynamic Life Cycle Emissions Approach

In order to enhance the environmental appraisal of potential future UK ESI systems, a more dynamic LCA methodology was applied in this paper to investigate the likely environmental implications of the gas supply fuel evolution out to 2050. Consequential (change-oriented) LCA methodology was used to investigate the environmental implications of these likely potential choices [26] over time, in order to limit risk when undertaking strategic technological selection. Consequential LCA evaluates the change in flows in respect to a given decision or market, and subsequently the corresponding change in environmental impact beyond the foreground system.

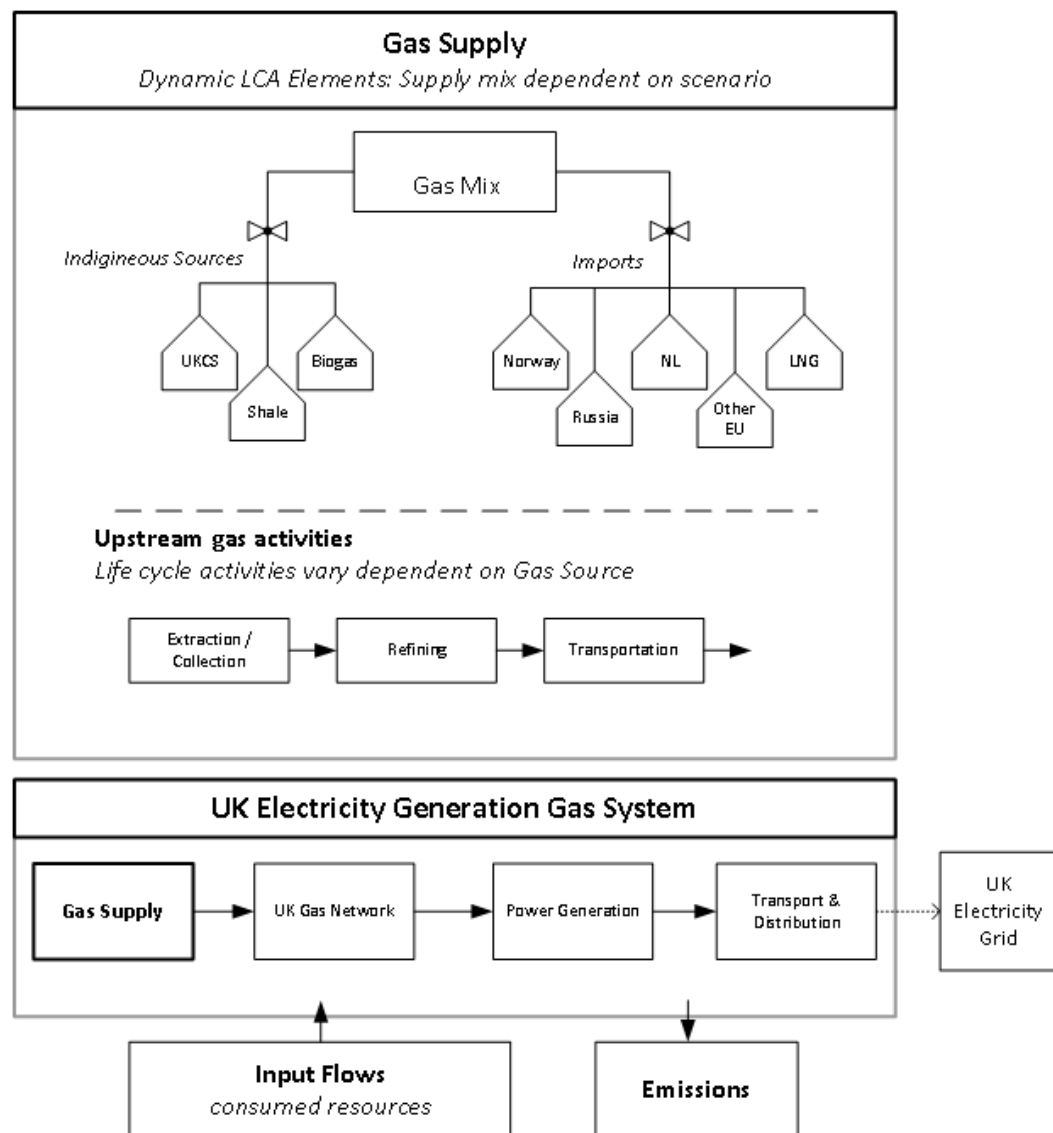


Figure 1 -System boundaries of the dynamic elements of the UK electricity generation gas system

In this paper, the reduced availability of domestic natural gas supplies causes a shift in demand for new sources of gas, such as shale gas and biomethane. These gas resources have different associated activities and processes, outside the original boundary of the product system (see Figure 1), with a subsequent change in GHG emissions. The UK gas supply will depend on future contracts negotiated based on technical, political and economic factors. Ultimately, the consumed gas will be chosen based on the least cost, most secure and viable supply chain. The implications of these potential decision-makers' choices for the future UK gas supply are explored in this study.

Both consequential and attributional methodologies of LCA provide valuable policy support [27-29] and can be applied when modelling future systems. Attributional LCA provides a broad overview of environmental consequences of a future system, whereas consequential LCA provides insight into the influences of decision makers, and the nature of a product chain on future systems. The insight provided by both methodologies are invaluable as policy makers and regulators attempt to address multiple environmental goals. Together, they can provide a more rounded environmental assessment within a wider socio-techno-economic assessment framework [24]. Such analysis will help guide policy-makers and other stakeholders when investing in new generation technologies and considering their GHG performance as part of the so-called energy policy 'trilemma' [7, 30], i.e., the simultaneous delivery of low carbon, secure, and affordable energy services.

This analysis builds on the preceding attributional life cycle GHG assessment of the UK electricity system, from 'cradle to gate', for the three different Transition Pathways. In the baseline analysis, all data and assumptions were based on current prevailing technology, providing a static snapshot appraisal of the UK electricity system. The life cycle impacts of the UK power generators specified in these transitions, were determined using LCA datasets populated with real-life data compiled from current operational power plants. For more novel technologies, such as tidal and wave, proxy datasets have been adapted in accordance with studies of these technologies [31, 32]. Appreciably, significant uncertainties arise when assessing a future system, such as potential technological advances and variations in fuel supply source over time. Here, the dynamics in the gas supply source (see gas supply box in Figure 1) are explored to evaluate its potential implications on the GHG performance of the electricity sector. The system boundaries of this assessment were defined as 'cradle-to-gate' electricity provision (see Figure 1). All upstream processes were included from material extraction, manufacturing, transportation, and construction of the power plant. The downstream boundary was taken as the point of delivery to the electricity transmission grid. The latest Transition Pathways (version 2.1) were used as the basis for this investigation (i.e. the baseline system) into the gas supply evolution over time. The *Digest of UK Energy Statistics* (DUKES) allocation for fuel, which assumes that it requires twice the fuel to generate electricity, as to produce

heat [33], was used to allocate emissions associated with ‘Combined Heat and Power’ (CHP) plants. This allocation was used to reflect the resource’s value as both an electricity and heat provider.

Three potential future gas mixes were developed to explore their impact on the future UK ESI emissions, based on projected gas trends, market developments, and future production insights, as outlined in section 2.2. The three future gas mixes were paired with the three Transitions Pathways (in place of the 2012 gas supply mix), allowing their impact on a potential future UK ESI to be investigated through nine potential energy future scenarios. In order to limit the level of uncertainty in this analysis, it was assumed that these supply chains (i.e. gas upstream processes) would be the same as the current route. The gas supply upstream systems (see Figure 1) vary only in terms of their relative contribution to the overall gas supply, with all underlying assumptions remaining the same out to 2050. The only exception is for biomethane production, where the feedstock mix evolved over time (see Table SI_6), although again, the underlying assumptions for each feedstock resource group remain unchanged.

The global warming potential (GWP) of GHGs were measured in kilograms of CO₂ equivalent (kgCO₂eq) and benchmarked in accordance with figures published by the IPCC[34] [*Fourth Assessment Report* (AR4), 2007] on a 100 year time horizon. Despite the recent AR5 updated GWPs, the data for gas sources were reported in aggregate CO₂eq emissions based on AR4 GWPs over a 100 year time horizon, which was applied across the system to maintain consistency. Emissions data for natural gas imported by pipeline from Norway, the Netherlands, wider EU continent and Russia were taken from the *Ecoinvent* database version 2.2 [35]. Data was collated from various studies from literature to account for LNG and shale gas supply routes [35-40].

The current UK feedstock mix for anaerobic digestion was employed when accounting for emissions associated with biomethane production. Scenarios developed by Welfle *et al.* [41] of the UK bioenergy potential out to 2050, were used to model the change in feedstock contribution over time. The range in emissions for these mixes were calculated based on data from literature for these feedstocks [35, 37]. Biogenic carbon emissions emitted during the combustion of biogenic feedstock is equivalent to the carbon absorbed during the growing of that same feedstock. Where the cultivation of feedstock has been sustainably managed, it is considered a carbon neutral process over the course of the bioenergy system life cycle. Conventionally, as stated in the IPCC guidelines [42], such biogenic emissions are not accounted for within the energy sector, but rather anthropogenic variations in carbon stocks are accounted through land use change. Such an approach was adopted here in order to avoid double-counting of emissions. The biogenic emissions captured through use of CCS have been treated in the same manner as captured fossil emissions, and modeled as an offset, having both being prevented from release into the atmosphere. [An account of the data collection for

the various gas supply pathways, and assumptions taken are included in *Supplementary Information* section 1.]

2.2 UK Gas Supply Evolution

Whilst the UK's domestic natural gas production (mainly North Sea) has declined in recent decades, imports with greater associated upstream emissions, have risen to meet the shortfall. Since the UK government doesn't currently account for these upstream emissions within the electricity sector [12], the change in the true carbon intensity of the UK electricity grid mix on a life cycle basis has not been well documented. Demand has been reducing over the past number of years, particularly for electricity generators, due to the relatively high gas price compared to coal [43]. However, given its flexibility, relative short project lead in times, and low capital cost, gas-fired power generators are set to remain a major component of the UK electricity system for many years to come [44]. In fact, The UK government recently announced an energy policy 'reset', which would see that all unabated coal-fired power stations were to close by 2025 [44], further emphasising the critical role of gas generation in the UK energy future. Today's UK gas mix (as of 2012) can be seen in terms of percentage shares in table 2. There are many external pressures at play which are likely to influence the UK market over the coming years [15, 45-47], such as increasing Asian demand, diminishing reserves in the European Union, and growth in unconventional gas sources (such as shale gas and biomethane). Norwegian and Dutch production are set to decline post 2015 [48, 49], leaving the UK progressively more reliant on imports of LNG and pipeline gas from mainland Europe, largely originating from the Russian Federation (Russian imports account for over 25% of consumed natural gas in Europe [50]). [These major trends are discussed in more detail in *Supplementary Information* section 2.] Furthermore, gas markets have proven to be rather susceptible to "black swan" events. These are low probability, high impact events that are hard to foresee [51]. The Fukushima nuclear disaster is a recent example of such an event, which resulted in a large demand for imported gas by Japan. Thus, in 2012, due to increased prices, UK LNG imports were down 50% than in the previous year.

Table 2. Future UK gas supply mixes by source

Source by percentage	2012	2020			2030			2050		
	Supply mix	Supply mix 1	Supply mix 2	Supply mix 3	Supply mix 1	Supply mix 2	Supply mix 3	Supply mix 1	Supply mix 2	Supply mix 3
UKCS	52.9	38.0	38.0	38.0	23.6	23.6	19	5.0	5.0	5.0
Biogas	0.0	5.0	10.0	5.0	5.0	18.0	5.0	5.0	25.0	10.0
Shale gas	0.0	9.6	0.0	0.0	34.4	0.0	0.0	60.0	0.0	0.0
Indigenous	52.9	52.6	48.0	43.0	63.0	41.6	24.0	70.0	30.0	15.0
Norway	25.9	30.4	30.4	30.4	20.6	20.6	20.6	140.0	14.0	14.0
Netherlands	6.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LNG	13.0	11.5	16.1	11.5	9.9	28.4	16.0	11.2	42.0	20.0
EU Continent	1.3	2.3	2.3	6.3	2.2	3.2	7.9	0.7	2.8	7.7
Russian	0.0	3.2	3.2	8.8	4.4	6.3	31.6	4.1	11.2	43.4
Imports	47.1	47.4	52.0	57.0	37.0	58.4	76.0	30.0	70.0	85.0
Total	100	100	100	100	100	100	100	100	100	100

2.3 Future UK gas supply scenarios

Three future gas mix scenarios have been developed, based on the future trends (as discussed in the previous section and in section SI_5), in order to explore the potential implications of a reshaping UK gas supply. These mixes have been developed for explorative means only, and do not attempt to predict or, particularly, imply the nature of the future gas market. Three sets of mixes have been generated for each supply scenario: a mix for years 2020, 2030 and 2050 respectively in order to explore the transition. The main assumptions and trends for each case study are outlined below, and their supply breakdown is provided in Table 2 [Further elaboration of underlining assumptions have been provided in *Supplementary Information section 3.*]

- **Supply 1: UK Shale gas ‘boom’.** In this future, it is assumed that shale gas extraction takes off and becomes the UK’s primary gas source. Reliance on other gas sources will reduce, with a stable contribution maintained in the interest of security of supply. In this future, it is assumed that LNG will be the main source of imports, although with Russian imports reduced, due to political tensions in that region. A moderate penetration of biomethane continues as part of the mix in order to utilise bio-waste.
- **Supply 2: High biomethane and LNG supply.** In the event of a shale gas moratorium across the whole of the UK, biomethane would be more heavily developed to provide an indigenous supply of gas. Again, in this future, it is assumed that LNG will be the main source of imports, but Russian imports again reduced because of political tensions in that region.
- **Supply 3: High Russian gas dependence.** This future assumes a shale gas moratorium in the UK. Biomethane is also limited, due to various likely environmental pressures (such as land use). In the absence of a shale gas supply, and constrained biogas, it was assumed that domestic UK conventional natural gas supply will be conserved over time in the interest of security of supply. Asian demand for LNG also increases dramatically, constraining this source. Consequently, Russia would become a critical supplier to Europe.

3 Results

3.1 Life cycle GHG emission intensity of future potential UK gas supply mixes

The GHG emissions associated with the three future gas supply mixes out to 2050 are presented in Figure 2. For all three supply mixes, the associated GHG emissions increase significantly out to 2050 as a result of the incremental diffusion of new gas sources with higher upstream emissions. The central estimate GHG emission intensity of these three supply mixes ranged roughly between 13 to 16 gCO₂eq/MJ in 2050, rising from the baseline of just under 5 gCO₂eq/MJ in 2012 (see figure 2). The high biogas dependence mix (supply mix 2) had the highest associated GHG emissions, representing a 3.4 times increase in GHG emissions on the 2012 UK gas mix. The high shale gas penetration mix (Supply 1), had the lowest central estimate of associated upstream emissions in 2050, representing a 2.7 times increase on emissions.

Russian pipeline gas has the largest associated uncertainty range of all the sources examined. This range was largely due to disparity in reported methane leakage rates in this region (ranging from 0.9% to 3.3 % of gas transported) [52]. For LNG and shale gas, the range in fugitive methane emissions rate also proved to be a key parameter, accountable for much of the uncertainty [35-40].

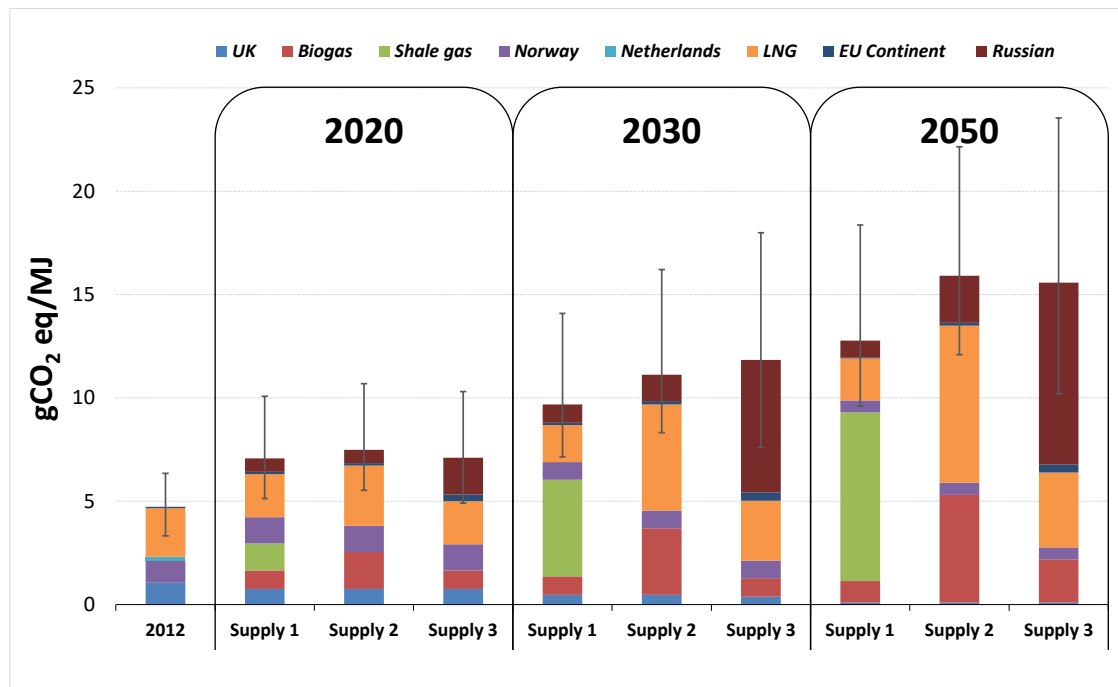


Figure 2. GHG emissions intensity of potential future UK gas supply mixes per MJ of fuel delivered. [Error bars represent the overall uncertainty range associated with each gas mix, see SI_section 2 for details]

In contrast, the range in GHG emissions associated with biomethane production, was primarily due to the variance in yield from feedstocks available [35, 37]. Since these supply routes all play a significant role in the future gas supply scenarios examined here, there is a considerable uncertainty range associated with all three mixes. [More details on the uncertainty analysis and other assumptions taken can be found in Supplementary information (SI) section 1]

3.2 Life cycle GHG emissions of the future UK electricity system

The life cycle GHG emissions of the transition pathways paired with the three future gas supply mixes are presented in Figure 3, Figure 4 and Figure 5 for MR, CC and TF respectively. The results are compared with the baseline results (using the 2012 gas mix) in these figures, to determine the impact of the gas supply transformation on the life cycle GHG intensity of the UK ESI. [The generation mix for each pathway, from 2008 out to 2050, can be seen in section S1.2]. The emissions have been broken into upstream gas, upstream other, and direct fossil emissions, to enhance the interpretation of the results. The upstream gas emissions are the GHG emissions associated with the gas production processes for the given gas supply (as highlighted in the gas supply box in Figure 1). ‘Upstream other’ emissions specified here, are all the GHG emissions upstream relating to the power sector (such as emissions associated with upstream coal and biomass supply, upstream materials and processing related with power generators construction, and their transport to site), excluding the upstream gas emissions. Direct fossil emissions are the GHG emissions resulting from the combustion of fossil based gas sources.

The gas supply evolution out to 2050 was seen to be influential over the cumulative results for all three pathways (see figure 3-5), but the degree in which they vary dependent on the gas supply mix employed. The high shale gas supply (Supply 1) resulted in the highest central estimate life cycle GHG emissions for all transition pathways, whilst the high biomethane and LNG supply (Supply 2) resulted in the lowest. The high Russian gas supply (Supply 3) life cycle emissions for the three pathways were only marginally lower than the high shale gas supply. Despite having the highest associated upstream emissions, the central estimates for all three pathways, paired with the biomethane and LNG mix (Supply2), in fact observed the lowest overall life cycle emissions, demonstrating the importance of taking a whole life cycle perspective. This was the result of a reduction in direct fossil GHG emissions owing to greater penetration of biomethane. In contrast, the *Thousand Flowers* (TF) pathway had similar results for all three gas supplies (see figure 5). This pathway is less dependent on gas generation in 2050 compared to MR and CC (see Figure SI_1-3 for the generation portfolios). Biomethane CHP is the dominant fuel based technology under The TF pathway, providing backup to the more intermittent technologies. The changes in GHG emissions in

TF were, therefore, largely the result of upstream emissions related to biomethane production, with only relatively minor influence from other gas sources.

The *Market Rules* (MR) pathway, when paired with Supply 1, gave rise to an increase in central estimate life cycle emissions of 6 million tonnes of CO₂eq emissions by 2050(see figure 3), while the *Central Coordination* (CC) pathway rose by 4.5 million tonnes of CO₂eq emissions (see figure 4), representing nearly a 10% and 14% rise above the baseline respectively. The central estimate life cycle emissions for the TF pathway, when paired with supply 1, experienced the greatest rise in GHG emissions of 7.3 million tonnes of CO₂eq emissions (a 24% rise above baseline), due to the increase in upstream emissions associated with biomethane out to 2050. This pathway only features a moderate level of gas-fired CCS generation by 2050 (see section SI_1.2), and therefore does not experience the same reduction in direct emissions as the other two pathways. In contrast, when paired with the Supply 2 (having the highest biomethane penetration), the lowest level of GHG emissions can be observed for all three pathways (see figure 3-5). MR and CC emissions drop by 0.5 and 0.3 million tonnes of CO₂eq emissions in 2050, while TF pathway emissions rose by 6.3 million tonnes above the baseline.

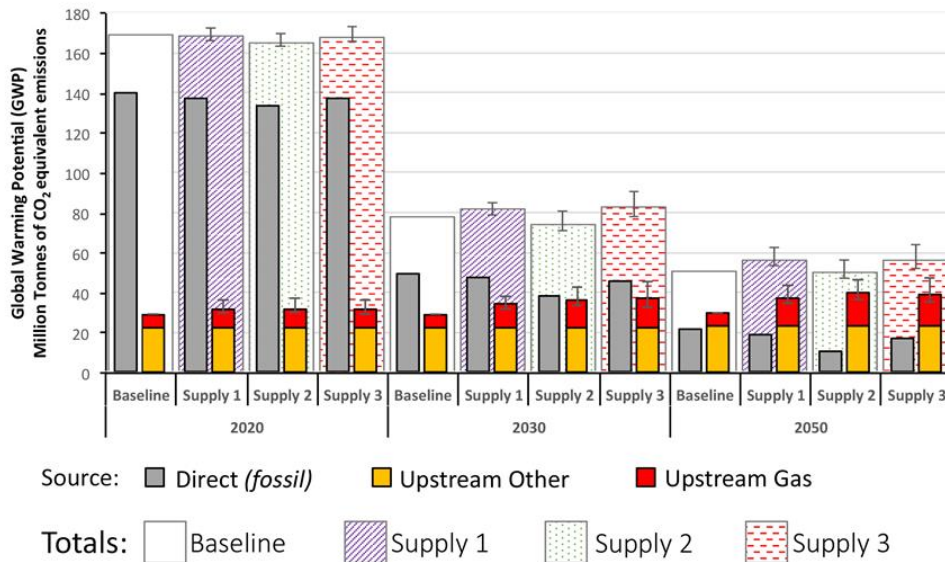


Figure 3. Total life cycle GHG emissions for the Market Rules (MR) Pathway when paired with the three future gas supply mixes. These emissions are then broken down into direct fossil, upstream other and upstream gas respectively. [Error bars represent the uncertainty range associated with each gas mix, see SI_section 1 for details]

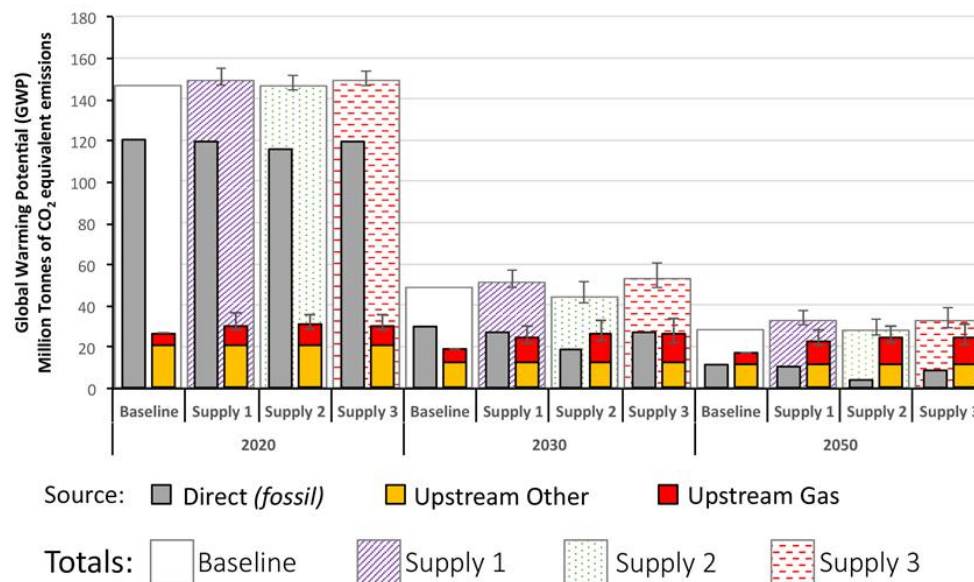


Figure 4. Total life cycle GHG emissions for the Central Coordination (CC) Pathway when paired with the three future gas supply mixes. These emissions are then broken down into direct fossil, upstream other and upstream gas respectively. [Error bars represent the uncertainty range associated with each gas mix, see SI_section 1 for details]

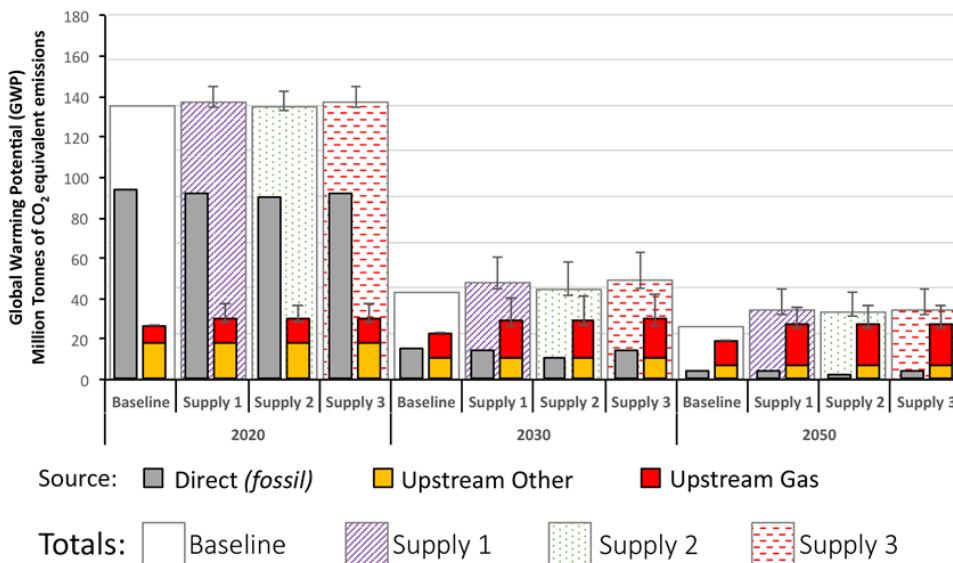


Figure 5. Total life cycle GHG emissions for the Thousand Flowers (TF) Pathway when paired with the three future gas supply mixes. These emissions are then broken down into direct fossil, upstream other and upstream gas respectively. [Error bars represent the uncertainty range associated with each gas mix, see SI_section 1 for details]

3.3 Impacts of gas supply transformation across life cycle stages

The gas supply transformation was seen to have varying impacts on different life cycle stages of electricity generation, from increase upstream emissions, to reducing direct fossil emissions through the influx of biomethane. For all three pathways, upstream emissions associated with gas supply were shown to increase considerably, due to the greater penetration of new gas sources with higher associated upstream emissions. The central estimates for upstream emissions associated with the gas supplies ranged from 11 to 20 million tonnes of CO₂eq emissions in 2050, accounting for 25% to 70% of total electricity sector emissions by the end of the transition. This represents an increase of between 6 and 8 million tonnes of CO₂eq emissions above baseline gas-related upstream emissions.

Direct fossil emissions were seen to reduce substantially (see table SI_14), from both fuel switching from natural gas to biomethane, and also the sequestering of biogenic emissions associated with biomethane-fired power generation with CCS. Reductions in the central estimate direct fossil emissions from the baseline, ranged between 0.3 and 1.6 million tonnes of CO₂eq emissions for the TF pathway, and between 2.1 and 10.6 million tonnes of CO₂eq emissions for its MR counterpart in 2050. Supply 2 and 3 exhibited this offset of emissions most strongly, with a share of 25% and 10% of biomethane in the gas supply mix by 2050 respectively. Nonetheless, more absolute emissions reduction was experienced in 2030 when gas-fired CCS played a more significant role in the pathways, despite lower penetration of biomethane in the gas supply mix.

The gap between direct fossil and total emissions, and hence the perceived and real GHG performance of the UK ESI, were seen to increase from the baseline system for each year examined as a result of the gas supply transformation. The absolute change in GHG emissions for each life cycle stage between the baseline gas supply and that of the Supply 1-3, for all three pathways, is shown in Figure 6, demonstrating the vulnerability of the UK ESI performance to the dynamics in gas supply and markets.

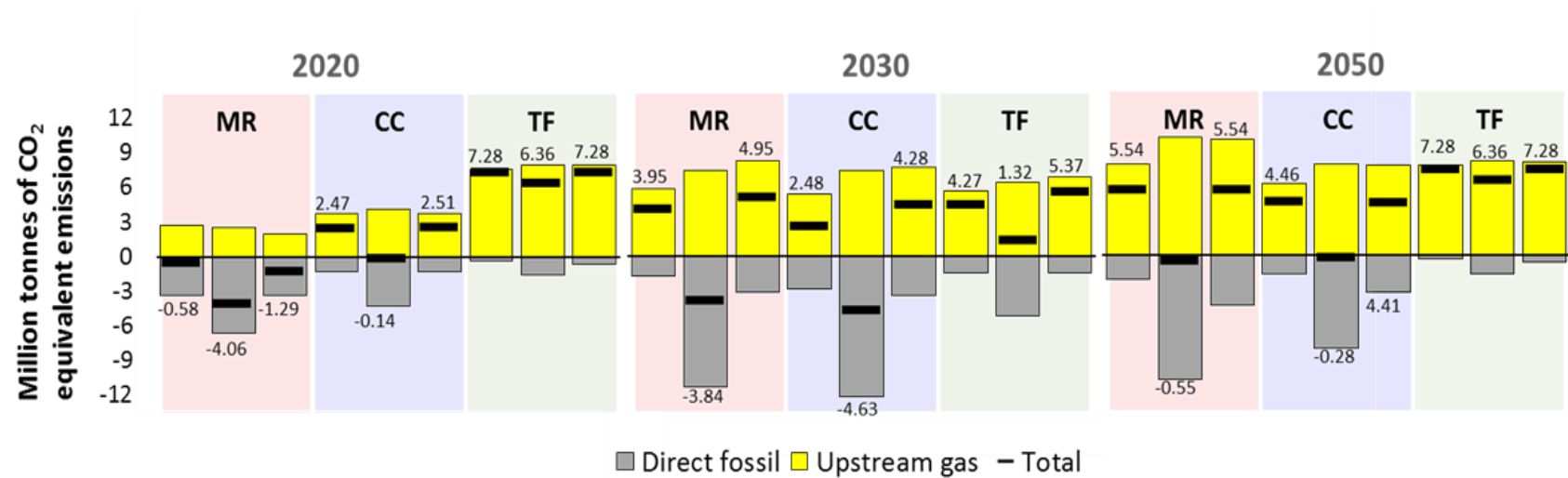


Figure 6. The absolute change in GHG emissions for different life cycle stages of electricity generation for the three Transition Pathways. The graph shows the disparity between baseline gas supply results (where zero represents the baseline) for the pathways and the results for supply 1-3 (from left to right).

4 Discussion and Policy Implications

The implications of a future UK gas supply transformation have been examined in this paper by developing three potential gas supply mix scenarios to explore the potential impact on climate change of the future UK ESI. Each mix represents different UK gas futures, dominated by particular gas resources. Supply 1 consists mainly of shale gas, Supply 2 is dominated by both indigenous biomethane and LNG imports, whereas Supply 3 is dominated by Russian natural gas imports. The 2012 gas mix used in the baseline assessment of the Transition Pathways was substituted with these three gas mix scenarios to investigate their impact on the overall GHG intensity of the UK ESI. This work builds on the attributional life cycle GHG emissions assessment of the technological trajectories of these Transition Pathways [16]. Together, they form a more comprehensive life cycle GHG assessment of the system than has been previously available which will could help to inform future decision-making.

Several significant conclusions can be drawn from the transformation in GHG intensity associated with the electricity supply in response to the gas supply evolution. The UK ESI GHG performance will become more dependent on gas supplies from far away regions with emissions of greater uncertainty. Central estimates suggest that total life cycle emissions of the UK ESI will increase, except where the penetration of biomethane is sufficient to offset rising upstream emissions. When the pathways were paired with Supply 1 (the most impactful mix), the central estimate of total emissions were seen to rise between 4.5 and 7.3 million tonnes of CO₂eq emissions by 2050, representing a 9.9% and 24% rise respectively compared to the baseline system. Direct emissions were seen to fall for all pathways, through the penetration of biomethane, particularly when used in conjunction with gas-fired CCS. The disparity in GHG emissions between the baseline gas supply, and that of the Supply 1-3 for the pathways for each life cycle stage is shown in Figure 6, demonstrating the vulnerability of the UK ESI performance to the dynamics in gas supply and markets.

Since decarbonisation of the electricity system is a critical climate change policy in both the UK and globally, better monitoring and mitigation of upstream emissions is needed to ensure that significant rises in GHG emissions are avoided. The UK National GHG Inventory only accounts for emissions that occur within the national boundary, although there still remains indirect emissions unaccounted for that occur overseas. Full accounting of gas related emissions is of particular importance in the UK, as its gas supply is set to undergo a large transformation over the coming years as domestic natural gas diminish [15]. Failure to account from these emissions, could make the electricity produced seem less impactful than reality, and could induce greater usage, resulting in adverse consequences that would not have been accounted for under current legislation.

A significant proportion of upstream GHG emissions were the result of fugitive methane emissions during production, transportation and distribution from all gas production routes. The range of fugitive methane rates reported in literature was responsible for much of the uncertainty associated with the gas sources. These fugitive emissions can be minimised with the correct procedural measures. This is increasingly critical in light of the most recent report by the IPCC which called for an increase to the GWP of methane from 25 to 34 gCO₂eq over a 100 year time horizon [53] for biogenic methane, and 36 over a 100 year time horizon for fossil methane, implying that it is a far more potent GHG than previously realised. The increase in gas upstream emissions shown here would be more severe should this new GWP for methane be applied. Reporting of disaggregated data in future work in this area, including a breakdown of GHGs emitted, would greatly enhance studies of this nature, and facilitate the adoption of the most current climate science thinking, and also assist greater scrutiny of key parameters of gas supply chains, such as transport distances and fugitive emissions rate.

The underlying data for shale gas GHG emissions were from US-based studies, and should only be considered 'indicative' until UK operational data becomes available. The Shale gas industry is now well established in North America; but transparent GHG emissions data is still scarce. It is imperative that accurate emissions data is collected at the earliest stages of UK operations, in order to assess the disparity with North American counterparts. Equally there are large uncertainties in GHG emissions associated with biomethane, since its feedstock could vary significantly over time, or from one season to the next.

This study highlights the vital role biomethane could play in the gas supply future in order to limit GHG emissions. It's inclusion in the supply mixes proved essential in offsetting the otherwise rising upstream emissions, particularly for MR and CC pathways that contain greater gas-fired generation. The high shale gas supply (Supply 1) was disadvantaged by the low penetration of biomethane in the mix (see figure 3-5), resulting in the highest cumulative emissions for the UK ESI for all three Transition Pathways. Shale gas would assist in securing the UK's security of supply, but could hinder the growth of biomethane. There is little doubt that increased availability of low cost gas through the development of a UK shale gas industry could fundamentally re-order UK energy policies. The importance of developing and maintaining support for a strong UK biomethane production industry, regardless of the exploitation of shale gas, has clearly been demonstrated by the present study.

Both MR and CC pathways rely substantially on CCS to reduce their GHG emissions. Reduction in direct fossil GHG emissions was seen to be particularly large when CCS is used in conjunction with the combustion of biomethane. In the absence of large-scale CCS, the use of gas as a transition fuel

must be greatly reduced in order to adhere with carbon budgets. Consequently, any substantial investment in future gas-fired power generation should perhaps be deterred until CCS has reached maturity. This work demonstrates the critical role of gas CCS in the future UK energy system, highlighting the need to replace and strengthen CCS funding rapidly, in light of the recent cancellation of one billion (£1 bn) pound funding for CCS in the UK [54].

The gas supply transformation that will be experienced in the UK over the coming years will have much wider over-arching environmental implications than GHG emissions alone. All future supply mixes scenarios rely on alternative gas supplies, such as shale gas and biomethane. Both resources can provide gas at lower life cycle emissions than some of their more traditional counterparts, such as LNG and Russian imports, although they pose other significant environmental risks. The nascent shale gas industry has received attention for its wider environmental impacts, such as groundwater and surface contamination, land contamination, water consumption and seismic impacts [55, 56]. Similarly, biomethane production can result in large water usage, land degradation and land conflict with the food sector [57]. Such environmental trade-offs must always be managed comprehensively, expanding on the sort of sustainability criteria originally established for biofuels in, for example, the EU's *Renewable Energy Directive* [58].

As new energy policies advance, and changes are implemented to the current power system, it becomes necessary to not only consider today's benefits, but to also examine the long-term dynamics. Ensuring that transitions embarked on now, will continue to be advantageous into the future. Relying on gas as a transitional fuel may result in GHG emission lock-in, with emissions increasing further as upstream emissions rise over the coming decades. The UK benefited from substantial reductions in emissions in the 1990s during the "Dash for Gas", and consequential reduction in coal generation. However, a greater uptake of gas-fired generation cannot continue to deliver these same benefits into the future, particularly as it may impede the rate of deployment of low carbon technologies [4, 59].

5 Conclusions

Developed nations are increasingly switching from coal to gas-fired generation in an effort to mitigate climate change. The demand for gas is projected to rise in response to fulfilling this role as a bridging fuel to a low carbon future [4]; providing dispatchable back-up generation to balance the growth in renewables. As such, gas generation is anticipated to play a critical role in the UK energy future, further compounded by the recently announced complete phase out of coal generation by 2025 [44]. Concurrently, indigenous conventional gas production, already insufficient for the nation's needs, are set to diminish further which will result in a large transformation of the UK gas supply. This reshaping of the gas supply was shown in this paper to have considerable bearing on the

life cycle greenhouse gas (GHG) emissions of UK electricity generation which is currently not fully addressed by legislation [16].

A key finding in this research was that the UK electricity supply industry (ESI) GHG performance will become more dependent on gas supplies from far away regions, with higher associated GHG emissions than the current gas mix; which are also subject to greater uncertainty. Overall, when the three gas supply mix scenarios were paired with the *transition pathways* three low carbon electricity futures for the UK, central estimates suggest that total lifecycle GHG emissions of the UK ESI will increase compared to the baseline, unless the penetration of biomethane within the gas supply is sufficient to negate the rising upstream emissions. Upstream emissions were seen to rise substantially from the baseline by 2050, increasing by between 6 to 8 million tonnes of CO₂eq of additional GHG emissions. By the end of the transition, these gas-related upstream emissions accounted for between 25 to 70 % of total electricity sector GHG emissions, compared to just 3% for the current system. The carbon credit afforded by the influx of biomethane (particularly when combined with CCS), led to a coinciding reduction in direct fossil emissions. Consequently, the gap between direct fossil and total GHG emissions for the UK ESI was seen to grow in response to the gas supply transformation. Hence the direct GHG intensity of UK electricity (its perceived performance) appeared lower for all three pathways than the baseline, despite total life cycle emissions (its real performance) being in fact higher for both the high Shale and the high Russian gas supply mix, or of a similar level for the high biomethane and LNG gas supply mix. These results demonstrate the importance of considering the comprehensive total lifecycle GHG impacts of electricity generation, rather than just direct fossil ('stack') emissions, when developing and implementing new decarbonisation policies.

In the absence of adequate support to develop both a strong carbon capture and storage [6] and biomethane production industry, the future of gas generation in the UK must be reevaluated. Gas cannot act as a bridging fuel without these technologies to help curtail GHG emissions, as the system would become locked into emissions far higher than required levels. The carbon credits associated with biomethane proved essential in offsetting the rising upstream emissions, particularly for the *Market Rules* and the *Central Coordination* pathways which contain greater gas-fired generation. Consequently, disadvantaged by the low penetration of biomethane, the high shale gas supply examined in this paper proved the most impactful; despite lower associated upstream emissions than its LNG and Russian gas counterparts. Most critically, particularly in light of a recent funding failure [6], extensive investment in new gas capacity in the UK should be deterred until CCS reaches maturity. Only when these technologies reach full scale deployment, both negating rising upstream emissions and curtailing direct emissions, can gas truly play a part in the transition to a low carbon future.

Acknowledgements

This is a revised and extended version of a paper originally presented at the 9th Conference on Sustainable Development of Energy, Water, and Environmental Systems (SDEWES), Venice-Istanbul, 20-27 September 2014 [Paper SDEWES2014.0365]. Professor Geoffrey P. Hammond is jointly leading a large consortium of university partners funded by the UK *Engineering and Physical Sciences Research Council* (EPSRC) entitled '*Realising Transition Pathways: Whole Systems Analysis for a UK More Electric Low Carbon Energy Future*' [under Grant EP/K005316/1]. Áine O'Grady is wholly funded via this grant. Both authors are grateful for the interaction with other members of the Consortium (and its predecessor) made up of participants from nine UK universities. However, the views expressed here are those of the authors alone, and do not necessarily reflect the views of the collaborators or the policies of the funding body. The authors' names are listed alphabetically.

Abbreviations

CC	Central Coordination
CCC	Committee of Climate Change
CCS	Carbon Capture and Storage
CHP	Combined heat and power
DECC	Department of Energy and Climate change
DUKES	Digest of UK Energy Statistics
EPSRC	Engineering and Physical Sciences Research Council
ESCO	Energy services company
ESI	Electricity Supply Industry
GHG	Greenhouse gas
GWP	Global-warming potential
HV	High voltage
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LNG	Liquefied natural gas
MR	Market Rules
NGO	Non-governmental organisation
PV	Photovoltaics
TF	Thousand Flowers
TP	Transition Pathways
UKCS	United Kingdom Continental Shelf

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9.6 Key Outputs

The implications of a future UK gas supply transformation was investigated in this paper by developing three potential gas supply mix scenarios for the UK, and exploring their impact on the GHG emissions from the UK electricity sector. The penetration of both shale gas and biomethane in the gas mix were also explored, meeting objective 5 of this thesis.

It was found that The UK electricity sector will become more dependent on gas supplies from far away regions, which are subject to greater uncertainty, and higher associated GHG emissions than the current UK gas mix. The life cycle GHG emissions of the UK electricity sector for the *Transition Pathways* when paired with the three gas supply scenarios was determined in this paper, thereby contributing to the delivery of objective 2 and 6 of this thesis. Central estimate life cycle GHG emissions of the UK electricity sector suggest that they will increase compared to the baseline, unless the penetration of biomethane within the gas supply is sufficient to negate the rising upstream emissions.

Upstream emissions were seen to increase substantially from the present day for all three gas supply mix scenarios, increasing by between 6 to 8 million tonnes of CO₂eq by 2050. The carbon credit afforded by the influx of biomethane (particularly when combined with CCS), led to a coinciding reduction in direct fossil emissions. Consequently, the gap between direct fossil and total GHG emissions for the UK Electricity sector was seen to grow in response to the gas supply transformation. Therefore the significance of upstream emissions (addressing objective 3 of the thesis) in relation to the overall GHG performance of UK electricity is seen to grow over time. The direct GHG intensity of UK electricity (its perceived performance) appeared lower for all three pathways than the baseline, despite total life cycle emissions (its real performance) being in fact higher for both the *high Shale* and the *high Russian* gas supply mix, or of a similar level for the *high biomethane and LNG* gas supply mix. These results demonstrate the importance of considering the comprehensive total life cycle GHG impacts of electricity generation, rather than just direct fossil ('stack') emissions, when developing and implementing new decarbonisation policies.

This analysis also highlights the vital role biomethane could play in limiting GHG emissions from future gas electricity generation, and thus contributes to objective 5 of this thesis. Although biomethane was seen to have higher associated upstream emissions than its counterparts, it proved crucial, even at moderate levels, in offsetting direct emissions. Consequently, the high shale gas scenario in this study resulted in the highest overall greenhouse gas emissions for all three UK electricity system futures by circumventing the greater adoption of biomethane. This research also demonstrates the critical role of gas CCS in the future UK electricity system. Extensive investment in new gas generation capacity should be deterred until CCS reaches maturity.

10 Article VII – ‘The potential environmental consequences of shifts in UK energy policy that impact on electricity generation’

10.1 Journal Paper

G. P. Hammond and Á. O'Grady, 2016. *'The potential environmental consequences of shifts in UK energy policy that impact on electricity generation'*, *Proc IMechE Part A: J Power and Energy*, in press.

[DOI:10.1177/0957650916675519](https://doi.org/10.1177/0957650916675519)

10.2 Contribution to Research:

The Government has announced a succession of energy policy shifts over the course of 2015, signifying a ‘new direction’, or ‘reset’, for UK energy policy. Examples of such policy shifts are the announcement of the closure of all unabated coal generation by 2025, and the withdrawal of critical funding to enable carbon capture and storage [54] to reach commercialisation. These policy shifts represent profound change for future UK electricity generation; however their full environmental implications are relatively unknown. To the best of the authors’ knowledge, this paper represents the first endeavour to evaluate the environmental consequences of these policy changes on the future UK electricity system, and accordingly, meets objective 6 of this thesis. Whilst this analysis has been carried out in a UK context, its findings and insights have international relevance for other electricity systems, particularly within industrialised countries.

Three socio-technical energy ‘scenarios’ for the UK, known as the *Transition Pathways*, were employed to explore the impact of these policy shifts on the future UK electricity sector. Environmental life cycle assessment was used to evaluate the latest version of the *Transition Pathways* to act as a base reference case. This analysis thereby contributes to the delivery of objective 2 of this thesis, providing an evaluation of life cycle energy, GHG and environmental impacts on the future UK power sector. The three UK energy futures incorporating disruptive technological options were evaluated based on the phase out of coal use in favour of gas-fired power, ranging penetration levels of CCS, and the allocation and fuel type used for CHP plants. The results of these sensitivity analyses were then contrasted with that of the original *Transition Pathways* so as to assess the environmental consequences of these energy policy shifts.

10.3 The Significance and Originality of the Article

This research is the first to evaluate the long term environmental impacts of significant policy shifts, enacted and discussed during the 2015-2016 period, concerning the UK electricity system.

Furthermore, the full GHG emissions reduction potential of these policies was investigated, particularly as the system continues to evolve. Salient recommendations for policymakers were determined to not only devise better decarbonisation policies, but also to limit resulting wider environmental repercussions.

10.4 Contribution by Candidate:

Main author (generating 95% of content)

The candidate developed the concept and design of this paper, and carried out all experimental work and acquisition of data. The candidate drafted the full manuscript, with critical revision and guidance provided by the other author. The final review of the paper was also conducted by the candidate.

Title: The potential environmental consequences of shifts in UK energy policy that impact on electricity generation

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Abstract

Internationally there has been a move by nations to decarbonise their electricity systems in an effort to tackle rising territorial emissions. No consensus has been fully reached on best approach which has led to significant divergence in energy policy between countries and a consequential lack of long-term clarity. Additionally, recent United Kingdom (UK) policy failures, in terms of stimulating greater energy efficiency and encouraging energy innovation, highlight the huge challenge involved in developing and achieving a low carbon future. Steps to decarbonise electricity whilst also providing a secure and affordable supply, can lead to varying life cycle environmental consequences. A UK research consortium developed three pathways to explore this move to a more electric low carbon future out to 2050. These pathways have been previously evaluated in terms of their life cycle energy and environmental performance within a wider sustainability framework. Over the course of the project, greater understanding of the generation technologies and the functionality of the overall system under the different regimes were gained. Here, the environmental consequences of the most recent version of the pathways are presented on a life cycle basis from 'cradle-to-gate'. Thus, the environmental impact of technological trends in UK energy policy and their effect on the pathways are explored through a series of sensitivity analyses. The three UK energy futures incorporating 'disruptive' technological options were examined based on the phase out of coal use in favour of gas-fired power, ranging penetration levels of carbon capture and storage, and the allocation and fuel type used for combined heat and power. Recommendations are proposed to help frame future energy policy choices in order to limit the environmental consequences of future electricity systems.

Keywords

Electricity futures, Life cycle assessment, Sustainability, Carbon capture and storage, Fossil fuels, Bioenergy, Policy shifts

1 Introduction

Over the past decade, energy policy in the United Kingdom (UK) has been driven by three fundamental objectives which are; to deliver an affordable, secure and sustainable energy system; more commonly known as the ‘energy trilemma’^{1,2}. The relative importance of each objective has changed over time leading to various energy policy shifts³. Since the Climate Change Act in 2008, climate change mitigation has received substantial attention⁴. This Act places a legal obligation on the UK government for an 80% reduction in greenhouse gas (GHG) emissions from a 1990 baseline across the economy by 2050. Significant progress has been made in the interim period, which saw renewable sources grow to 7% of total energy consumed⁵. This rise was mainly the result of a series of green policy instruments implemented to support the growth of renewable energy; such as, the Feed-in Tariff scheme, Renewables Obligation, and Renewable Heat Incentive. As a result, national territorial GHG emissions are 36% lower than 1990 levels⁶.

Decarbonisation of the electricity sector has played a central role in reducing the UK’s GHG emissions, through initial fuel-switching from coal to natural gas, followed by the recent influx of renewables⁷. The *Committee on Climate Change* (CCC), an independent, statutory body providing evidence-based advice to the UK Government and Devolved Administrations, has long advocated that early decarbonisation of this sector is crucial in order to meet the UK climate change targets, with all associated GHG emissions largely eliminated by 2050^{7,8}. Currently, the electricity sector still accounts for 122Mt CO₂e, equating to 24% of total UK GHG emissions⁹. Recent energy policy announcements have seen the focus shift from climate change, towards affordability and security^{3,10}, in response to rising energy prices, economic recession and energy security concerns. Nonetheless, the UK government remain committed to targets, and are currently developing legislation for the fifth carbon budget⁷.

A succession of green policy interventions have been reversed in recent months¹¹ to make way for a new direction, or ‘reset’, for UK energy policy¹⁰ (particularly regarding electricity generation). The UK Energy and Climate Change Secretary, Amber Rudd, recently announced that all unabated coal-fired power stations were to close by 2025, and that their usage would be restricted from the year 2023, in order to reduce GHG emissions¹⁰. This would represent a seismic shift for the UK power sector, as coal generation currently accounts for 30% of total UK electricity generation⁵. Following the government’s Autumn Spending Review, the *Department of Energy and Climate Change* (DECC) have also scrapped a £1 bn funding competition aimed at bringing commercial-scale carbon capture and storage¹² to market in the UK¹³. This move was seen as a major setback for the UK CCS industry, raising serious doubts over its future, halting the progress of all planned UK carbon capture projects¹². The implications of such energy policy shifts on both climate change targets, and wider environmental concerns have yet to be determined, although it is widely

recognised (by bodies like the CCC and the public-private *Energy Technologies Institute*) that the potential national costs of carbon mitigation could double without CCS⁹.

Deeper decarbonisation of the electricity sector is envisaged to be achieved through the increased use of bioenergy¹⁴⁻¹⁶. Bio-sourced alternatives can be substituted for all fossil fuels, reducing society's dependency whilst also reducing their GHG emissions, and providing necessary back-up to more intermittent renewables^{16 17}. The deployment of combined heat and power (CHP) fuelled by biofuels is predicted to grow over the coming years in the UK, as measures are taken to decarbonise both the heat and electricity sector¹⁸. Its high fuel efficiency helps maximise the exploitation of a bioenergy resource. However, developing a long-term policy framework to incentivise large-scale bioenergy supply chains, which are both sustainable and economical, has proven to be a difficult undertaking¹⁹. This lack of policy certainty adds to the uncertainty over the availability of sustainable biomass resources, and makes it challenging to both suggest how this sector may develop and to forecast which bioenergy pathways will prove most effective.

The contribution of this paper is to provide a full understanding of the environmental life cycle consequences associated with large technological policy shifts in a decarbonising electricity system. In parallel, the implications of the resulting systemic change in delivering the Nation's long-term carbon targets were also explored. The merits of enacting potential policy shifts have been investigated in this paper from an environmental perspective, particularly in the context of electricity system undergoing a major transformation. Previous research in this area has primarily focused on examining uniform technological trajectory change^{20, 21} to meet a specific climate policy objective. Consequently, the impact of shifting energy policies on the development of future electricity generation systems, have been largely overlooked.

Three socio-technical energy scenarios for the UK, known as the *Transition Pathways*, were employed to explore the impact of these policy shifts on the future UK electricity sector. The environmental impact of shifting technological trends in UK energy policy and their effect on the pathways are examined through a series of sensitivity analyses. The three UK energy futures were assessed incorporating different energy policy options, such as, the phase out of coal use in favour of gas-fired power, ranging penetration levels of CCS, and different bioenergy supply chain for renewable CHP plants. These sensitivities analyses do not attempt to predict the full response of the system to these policy shifts but rather provide an indication of their potential environmental consequences for the future UK electricity sector. This work builds on the previous environmental life cycle appraisal of the *Transition Pathways*^{22 23}, which has been enhanced in the interim. The lifecycle environmental impacts of these pathways were first fully evaluated in order to act as a base reference case for comparison, denoted in this paper as the 'original' pathway.

Whilst this analysis has been carried out in a UK context, its findings and insights have international relevance for other electricity systems, particularly within industrialised countries. Similar shifts in energy policy may be witnessed internationally as the world's energy supply transforms in an effort to mitigate climate change. The findings of this paper could help to frame future energy policy choices in order to limit the environmental impact of the future electricity systems.

The paper begins with a brief introduction to the development of the *Transition Pathways* in Section 2, followed by a description of the methodology and assumptions taken in Section 3. The results of the environmental assessment of the original pathways are presented in Section 4, followed by the results of the series of sensitivity analyses to assess the environmental consequences of these energy policy shifts in Section 5. Finally, the implications of these results for the future UK electricity sector are discussed in Section 6.

2 Development of the *Transition Pathways*

The *Transition Pathways* consortium consisting of nine university partners was established to explore potential more electric, low carbon transitions in the UK power sector out to 2050. The consortium aim was to provide interdisciplinary analysis of the electricity system development in response to different decarbonisation approaches, including the potential for increasing use of low-carbon electricity for heating and transport. . Three socio-technical *transition pathways* were developed by this multidisciplinary team as summarised in Table 1 [1]. Each pathway was driven by different governance logics concerning the UK power sector; specifically market, central government, and civil society framings respectively. Analytical tools were developed and applied to assess the technical feasibility, social acceptability and environmental and economic impacts of the pathways.

The Three *Transition Pathways* storylines were first developed through stakeholders workshops, including representatives from policy, energy companies and non-governmental organisations ²⁴. A more detailed account of their development can be found here ^{1, 25}, with the full storylines available online ²⁶. The technical elaboration of these storylines were subsequently carried out by an interdisciplinary team (known as the *Technical Elaboration Working Group*) to provide quantitative representation of the storyline, expanding and further developing the socio-technical storylines in order to support detailed technical examination of these energy futures.

An iterative approach was taken to produce a quantitative representation of the storyline, feeding in findings from ongoing research, to develop increasingly encompassing quantitative representation which were more coherent and consistent. Two main interdisciplinary research streams were used to interrogate the initial quantitative representation of pathways.

Table 1. *Transition pathways overview: adapted from Foxon*¹

	Market Rules (MR)	Central Co-ordination (CC)	Thousand flowers (TF)
Governance	Market logic	Government logic	Civil society logic
Key technologies	Coal and gas CCS; Nuclear power ; offshore wind	Nuclear power; Coal and gas CCS; offshore wind	PV; Onshore & Offshore Wind; renewable Combined heat & power
Key trends	Limited interference in market arrangements; high level policy targets and high carbon price	Central government commission tranches of low-carbon generation from big companies to reduce risk of low carbon investment	Local, bottom-up diverse solutions led by local communities & NGOs, greater community ownership and more engagement of end-user
Electricity Demand	Increase demand for heating and transport Overall demand in 2050 (512TWh) much greater than today	Increase demand for heating and transport, but reduced through energy efficiency. Overall demand in 2050 (410TWh) slightly higher than today	Overall demand in 2050 (310TWh) lower than today. Higher rate of energy efficiency improvements and more aware consumers.

Firstly, a spectrum of cross-scale quantitative models (used to investigate and evaluated the pathways) was systematically linked to the *Central Coordination* storyline²⁷. The system boundaries and depth of analysis covered by these models were mapped, and the main area of expertise of each model was identified. The models were then tuned to match a set of harmonised assumption in line with the storyline, to allow inconsistencies in modelled results to be identified. Secondly, a detailed interdisciplinary assessment of the *Thousand Flowers* pathway, outlining the technical and institutional transformation required to support a move from a centralised to this highly distributed energy system¹⁷. The feasibility of this latter pathway was determined through a succession of interdisciplinary workshops, including input from community groups, OFGEM and external academics. The findings from this work were consolidated with insights from individual researchers' work across the project. Together they were utilised to guide the next iteration of the quantitative representation for all three pathways.

The identified irregularities and weaknesses were consolidated by the *Technical Elaboration Working Group* to produce a final quantitative representation of the pathways version 3.2 (which

acts as the reference case in this paper). The resulting pathways were far superior, comprehensive and more technically robust. Modifications which had a direct impact on the environmental performance of UK energy futures were: improved modelling of industrial CHP, increased installation rates for renewables (such as solar and offshore wind, reflecting more recent trends); greater back-up generation included to balance the system; more detailed modelling of community and micro CHP; the incorporation of alternative CHP fuel sources; new treatment of transmission and distribution system losses, and better representation of electricity demand on generators (particularly in regard to pumped storage).

3 Energy and Environmental Appraisal of the *Transition Pathways*

The environmental impact of the three transitions pathways (v3.2) [*Market Rules* (MR), *Central Coordination* (CC) and *Thousand Flowers* (TF)] for more electric low carbon futures were assessed by means of energy analysis and environmental life cycle assessment (LCA). LCA is an environmental management tool that quantifies the environmental impacts of a product, or system over its entire life cycle^{28, 29}. Every stage of the life cycle is systematically analysed from resource acquisition, production, through use and disposal.^{30, 31} This holistic approach, encompasses every stage, over a wide range of environmental impact categories, makes it a very useful comparative tool; potentially circumventing problem-shifting³². Energy analysis was conducted in parallel to LCA, accounting for the quantity of energy been consumed across the life cycle, differentiating its origin between non-renewable (e.g. fossil fuel) and renewable energy resources.

The appraisal of the *transition pathways* and their associated environmental burdens were evaluated, by means of two functional units; in terms of 1kWh of electricity produced, and related to the UK total electricity demand (e.g. in TWh). The system boundaries of this assessment were defined as ‘cradle-to-gate’ electricity provision (as shown in Figure 1). The ‘cradle-to-gate’ system boundaries included all upstream processes from material extraction, manufacturing, transportation, and construction of the power plant. The downstream boundary was effectively taken as the point of electricity end-use: delivery to the home, the commercial service provider, or to the factory. A range of assessment indicators were employed to quantify the environmental impact of the pathways with primary focus given to indicators such as GHGs and Cumulative Energy Demand (CED).

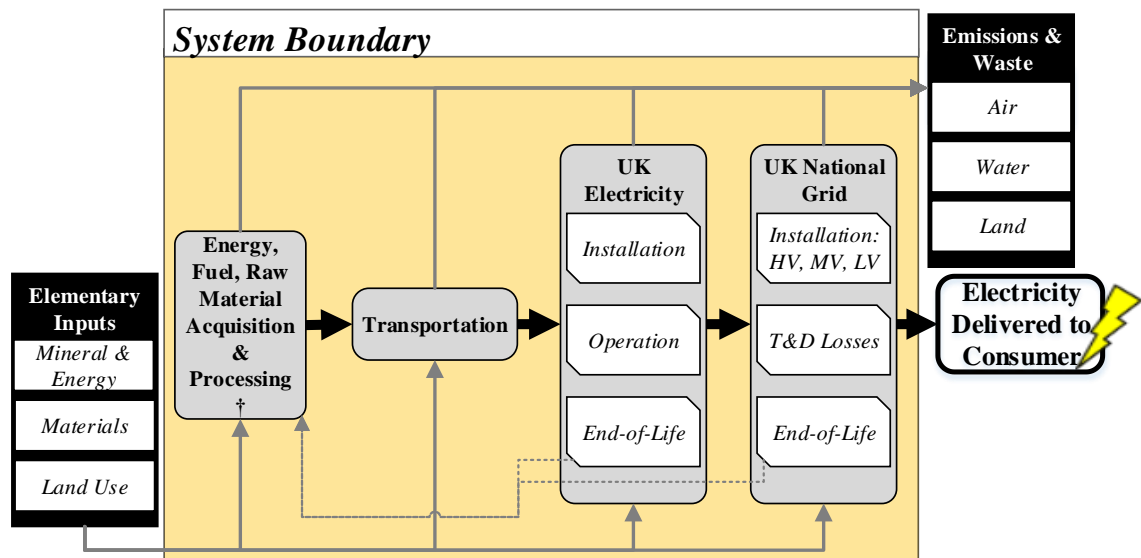


Figure 1. System boundary diagram for the life cycle assessment of UK electricity provision from ‘cradle to gate’

The global warming potential (GWP) of GHGs was measured in kilograms of CO₂ equivalent (kgCO₂eq) and benchmarked in accordance with figures published by the *Intergovernmental Panel on Climate Change* (IPCC) ³³ [in their *Fifth Assessment Report* (AR5) of 2013] over a 100 year time horizon. The ReCiPe life cycle impact assessment methodology was used in this study, employing 18 midpoint indicators, in order to account for wider environmental concerns [See Table SI_2 for overview of these indicators and their reference units] ³⁴. This methodology accounts for the GWP of GHGs (under the climate change category) in accordance with figures originally reported by the IPCC ³⁵ [in their *Fourth Assessment Report* (AR4) of 2007]; again on a 100 year time horizon. The AR4 GWPs were retained here (in contrast to the AR5 results), in order to assess the impact of advancing climate change science on the GHG intensity of the UK electricity sector. One of most significant changes made by IPCC between their AR4 and AR5 reports was the increase of the GWP of fossil methane from 25 gCO₂eq over a 100 year time horizon to 34 gCO₂eq for biogenic methane ³³, and to 36 gCO₂eq for fossil methane; this implies that it is a far more potent GHG than previously realised.

The life cycle impacts of the UK power generators, specified in these transitions, were determined using LCA datasets from the *Ecoinvent* database (version 2.2) ³⁶, populated with real-life data compiled from current operational power plants ^{37, 38}. For more novel technologies, such as tidal and wave, proxy datasets were developed in accordance with studies of these technologies ^{39, 40}. Current life cycle data for different generators was used to account for future plants and uncertainties in their technological improvements; an inherent limitation when carrying out future-oriented research.

International grid interconnection becomes increasingly important for all pathways, particularly TF (due to its highly distributed nature ¹⁷). Accounting for the impacts associated with electricity produced in interconnecting countries was outside the scope of this study. Instead, average impacts of domestic generation was assigned to net imports and included into total electricity generation. Improved community and new micro-CHP datasets were developed since earlier GHG accounting of the pathways ²², drawing on enhancements completed during the technical elaboration of the pathways. The modelled biogas supply was based on the current supply out to 2030 ⁴¹. Taking into account wider consortium research ¹⁷, there was an assumed 15% penetration of biomass gasification post-2030, with the remainder of the feedstock allocated according to current supply.

A series of sensitivity analyses were conducted to explore potential environmental consequences of UK energy policy shifts. The three UK energy futures incorporating disruptive technological options were examined based on the phase out of coal use in favour of gas-fired power, ranging penetration levels of CCS, and different bioenergy supply chain for renewable CHP plants. These energy policy choices, and the assumptions taken in modelling their impacts into the future, are outlined in the following sections. The results of these sensitivity analyses were contrasted with original results to assess the environmental consequences of these energy policy shifts.

The *Transition Pathways* were developed through a series of workshops with experts and stakeholders from policy, energy companies and non-governmental organisations ¹. The pathways development was also informed by various power system models and their technical feasibility (over various temporal load profiles across the year) verified by power system models to ensure system balancing⁴². Any changes to these tested pathways, greatly increases the associated uncertainty, and brings into question their technical feasibility. The sensitivity analyses have been performed for explorative means only, and do not attempt to predict how the system would precisely react to such policy shifts but rather indicate the range in their potential environmental implications.

3.1 Phase out of coal by 2025

The total phase out of unabated coal generation was recognised from the onset of the *Transition Pathways* research as a key requirement for a transition to a low carbon economy. As such, unabated coal generation is completely phased out of all three pathways by 2035, with only a minor contribution still present by 2030. Coal generation with CCS remains a key technology up until 2050 in the latest pathways (i.e., version 3.2), particularly in terms of providing dispatchable back-up generation to intermittent renewable technologies. Although the recent policy announcement does not necessarily rule out the use of coal CCS, a significant future for this technology out to 2050 is now considered unlikely, particularly in view of the increased uncertainty caused by recent CCS demonstrator funding cuts (see next section). A sensitivity analysis was carried out to explore the potential implication of transitioning all coal generation to gas generation (both unabated and with CCS), in line with policy reset speech by the UK Secretary of State for Energy and Climate

Change¹⁰. Both nuclear and gas generation were declared to be “central to our energy secure future” in this speech. However, it was recognised that a challenge with nuclear generation, as with other low carbon technologies, was to deliver nuclear power at a reasonable cost. No additional nuclear plants were assumed to replace the phase-out of coal generation as there were already considerable new nuclear power included in the generation portfolios of all three pathways. The installation of further plants, above this projected level of capacity, would be very unlikely, given the significant delays already experienced with the first planned new UK nuclear plant in decades⁴³. Although GHG emissions are the main focus here in terms of policy, the impact on the full spectrum of environment concerns has also been explored.

3.2 *The future of CCS*

The pathways were investigated with both 0%, and 50% penetration of CCS, with the remainder being modelled as unabated coal and gas, in order to explore the role of CCS in achieving future UK climate change targets. Only GHG emissions and CED have been considered in this sensitivity analysis. Other environmental impacts would vary in response to the fossil fuel used to meet additional load for CCS processes.

3.3 *Combined heat and power: Fuel source and allocation method*

In the initial appraisal of the environmental impacts of the *transition pathways*²³, all renewable CHP was modelled as biomass fired-CHP. Greater interdisciplinary analysis of the pathways using a whole system approach (particularly the in-depth examination of the *Thousand Flowers* pathway¹⁷), established that biogas was more likely be the dominant fuel type for CHP. A sensitivity analysis is carried out here to explore the consequences of both fuel types on the overall environmental performance of the *Thousand Flower* pathway. The TF pathway was examined because its results would be most influenced by the prevalence of CHP in this pathway.

A CHP system produces both heat and power, increasing the efficiency of fuel usage, and therefore reducing total costs and emissions. Three future electricity systems were compared in this assessment, requiring the environmental burden associated with these two energy co-products (i.e. electricity and heat) to be separated. Expansion of the assessment system boundaries to include the heating provision would circumvent this co-product issue, but this is not always plausible. This is particularly the case when a diverse range of technologies are utilised in different systems (which is the case here for the *transition pathways*). Furthermore, the generation of heat and power are often treated separately in energy policy in the UK¹⁷ as elsewhere. Selecting an appropriate allocation method would prove useful in guiding policymakers towards the most reliable and representative comparison of options.

No consensus has been reached within the LCA community on the best practice for allocation of these emissions, and it can generally depend on the particular application of a given CHP system⁴⁴. Various allocation methods can be applied, based on a range of considerations, from

thermodynamic performance to monetary value. Each are considered valid, but can bear a significant influence on results⁴⁵. In this assessment, the *Digest of UK Energy Statistics* (DUKES) fuel allocation method was employed to reflect the value of the resource as both an electricity and heat provider across the economy. The DUKES allocation method is based on typical efficiencies of CHP plants, and assumes that it is twice as hard to generate electricity as to produce heat. Energy and exergy allocation methods have also been applied here to explore their implications on results. Exergy allocation accounts for the quantity and quality of the energy streams, which results in most of the environmental burden being allocated to electricity (the higher quality output), which can produce more useful work. The energy allocation only accounts for the quantities of the two energy streams, with a large proportion of the environmental burden thereby being allocated to heat.

4 Environmental Appraisal of the Original Transition Pathways

The environmental impacts of the *transition pathways* (v3.2) are presented here, as a base reference case, from which the consequences of energy policy shifts on these future electricity systems can be explored.

4.1 GHG emissions

The MR pathway experienced the least decarbonisation by 2050, still emitting 63.7 Mt CO₂e on an annual basis. Comparatively, CC and TF, had much greater success; giving rise to 36.5 Mt CO₂e, and 37.8 Mt CO₂e in 2050 respectively. MR only achieves a 75% GHG reduction compared to 1990 emissions levels on a life cycle basis, whereas both the CC and TF pathways achieve around 85% reduction on the same basis. The remaining emissions reported in 2050 were largely the result of upstream emissions (highlighted in Figure 2), which have been previously explored in greater detail by the authors^{22, 46}. The CC pathway had the lowest life cycle GHG emissions, but only by a small margin: generating just 1.45 Mt CO₂e fewer emissions than the TF pathway on an annual basis by 2050.

Examining the three pathways in terms of per unit of electricity supplied (see

Figure 3), the CC pathway had significantly lower associated life cycle emissions than its two counterparts, resulting in only 88 g CO₂e/kWh. The MR pathway had the highest associated GHG emissions, emitting 121g CO₂e/kWh supplied, whereas the electricity supplied in the TF pathway had a GHG intensity of 107g CO₂e /kWh. Nevertheless, the TF pathway almost achieved the same level of decarbonisation exhibited by the CC pathway over the total system, despite having higher associated emissions per unit of electricity. These results demonstrate the significant role of demand reduction in lowering life cycle GHG emissions regardless of the performance of the technologies installed.

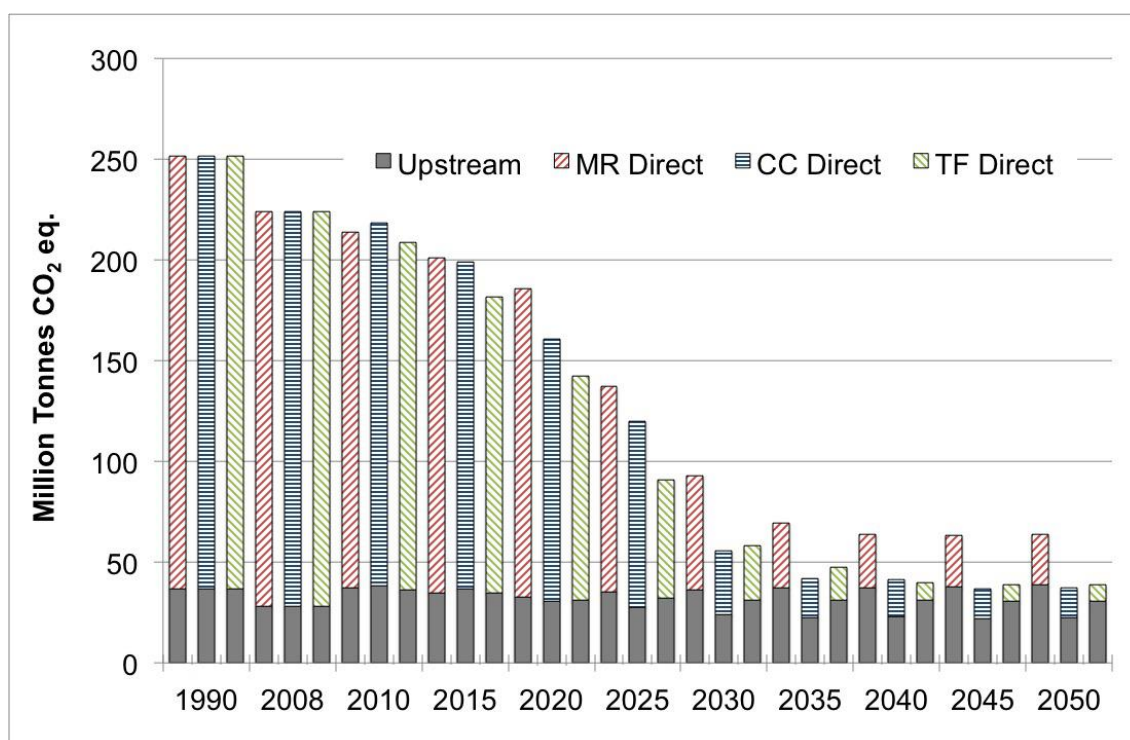


Figure 2. Total GHG emissions for the electricity sector (Mt CO₂e) 1990-2050 under the three transition pathways on a life cycle basis. (Upstream emissions have been highlighted. All remaining emissions emitted as direct emissions from generators)

Direct emissions from the three *transition pathways* in 2050 were 25.0 Mt CO₂e for MR, 14.6 Mt CO₂e for CC and 7.2 Mt CO₂e for TF. When considering only direct emissions, *Thousand Flowers* pathway is by far the most decarbonised pathway by 2050, reaching 97% reduction in direct GHG emissions compared to 1990 levels. This is considerably more than the 85% reduction experienced by the TF pathway on a life cycle basis. These comparisons highlight the importance of considering the full life cycle when assessing system change, and the inadequacy of considering only direct GHG emissions alone.

The MR and CC pathways also experienced greater perceived emissions reduction from 1990 levels, based on direct emissions alone; GHG emissions were seen to fall by 88% for MR pathway, and 93% for the CC pathway. Decarbonisation of the electricity sector at such levels suggest that all three pathways could play their part in achieving the statutory target of reducing 2050 national territorial direct emissions by at least 80% from 1990 levels⁴. Of course, this would require other sectors, such as heat and transport also to be predominately decarbonised on the same timescale.

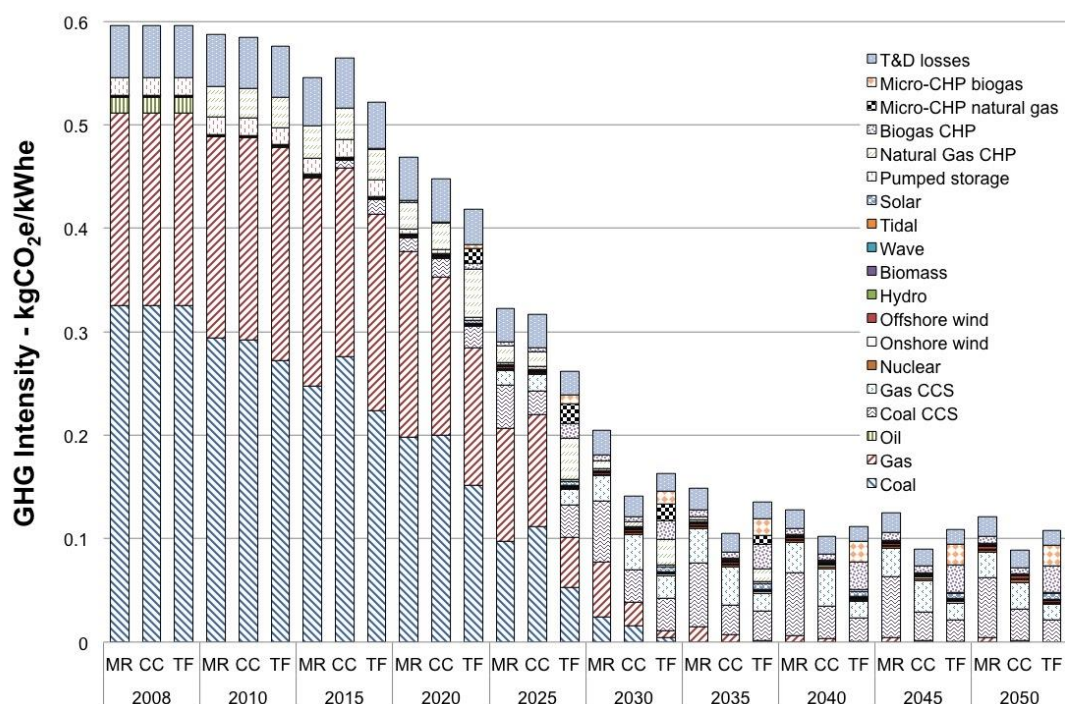


Figure 3. Contribution of each generating technology to overall GHG intensity of supplied electricity (kgCO₂e/kWh) under all three transition pathways, from 2008 to 2050.

Direct GHG emissions in 2050 ranged from 20-46 g CO₂e/kWh supplied, where the upper limit relates to MR, and the lower limit relates to the TF pathway. In the most recent power sector scenarios reported by the *Committee on Climate Change* (CCC), direct emissions were reduced to just under 100 g CO₂e/kWh for each of their three main scenarios by 2030⁹. Both CC and TF pathways experience greater direct emission reduction by 2030, only emitting 80 and 74 g CO₂e/kWh supplied respectively. Nevertheless, the MR pathway struggles to decarbonise sufficiently: emitting 124 g CO₂e/kWh supplied in 2030 on a direct emissions basis.

In the wider life cycle assessment, employing the ReCiPe life cycle impact assessment methodology of Goedkoop *et al.*³⁴, AR4 IPCC 2007 GWPs were purposely retained to compare with the updated results using AR5 GWPs. GHG emissions for the pathways using AR5 GWP factors were found to only be marginally higher than those reported using AR4 GWP factors. The MR pathway showed the largest difference of all three pathways, experiencing an increase of 1.53 Mt CO₂e over AR4 results. In contrast, the CC pathway displayed the least change, with GHG emissions only rising by 0.65 Mt CO₂e, whereas in the TF pathway these emissions rose by 0.74 Mt CO₂e. Both MR and TF pathways were influenced more strongly than their CC counterpart, owing to the higher penetration of gas-fired and biomass-fired generation in the former pathways (which result in greater associated methane emissions).

4.2 Cumulative Energy demand

The CED (see

Figure 4) for both the MR and CC pathways followed a similar trend to that of the overall electricity demand (see Table SI_1 and Figure SI_1). CED reached its lowest level in 2015 for the MR pathway, and in 2020 for the CC pathway, at around 3.6 and 3.5 EJ respectively.

The slightly delayed reduction compared to demand, was due to greater contribution of coal generation in the preceding period mixes, despite slightly lower overall electricity demand. The CED peaked at 5.24 EJ for the MR pathway by 2050, signifying a 37% rise on 2008 levels, whereas, a more modest peak of 4.07 EJ was realised by the CC pathway in 2050, representing only a 4% rise on 2008 levels. In contrast, CED for the TF pathway was seen to decouple from overall electricity demand, exhibiting steeper reductions than as a result of decreases in demand alone. CED was seen to continuously drop in the TF pathway (

Figure 4), as a consequence of the large reduction in non-renewable energy use.

Non-renewable energy demand (NRE) is the proportion of total energy demand across the life cycle of the electricity production that originates from non-renewable energy sources, such as fossil fuels (coal, gas and oil) and nuclear power. They represent the proportion of energy source completely consumed by the UK electricity sector, which cannot be renewed.

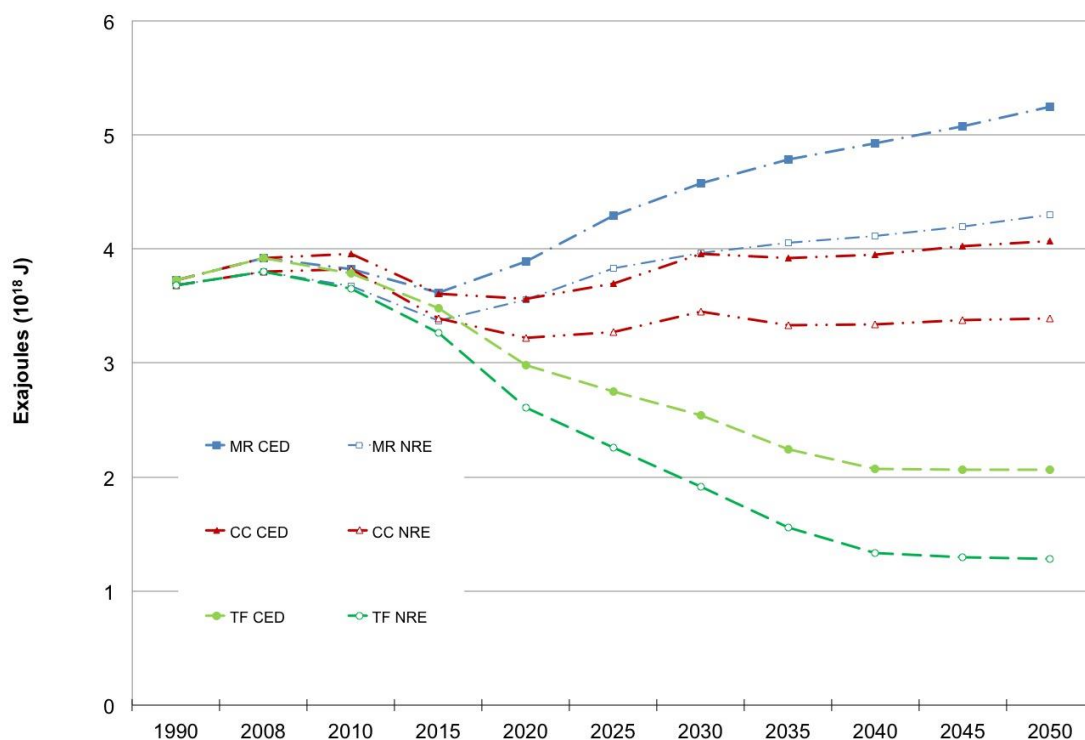


Figure 4. Cumulative Energy Demand for the UK electricity sector from MR, CC and TF pathways from 2008-2050. Both total Cumulative Energy Demand (CED) and Non-Renewable Energy Demand (NRE) are shown for the three pathways.

The MR pathway displayed the highest NRE as can be seen in Figure 4 (hitting 4.3 EJ by 2050), whilst TF had the lowest at 1.2 EJ. The NRE for the CC pathway was closer to that of MR, reaching 3.4 EJ by 2050. Despite the CC pathway having the lowest GHG emissions per kWh of all three pathways, it had the highest NRE per unit of electricity, consuming 8.1MJ/kWh supplied. MR was marginally lower at 8 MJ/kWh supplied, whilst the TF pathway consumed less than half that of its counterparts (at 3.6 MJ/kWh). The dominance of nuclear in the CC pathway, gives rise to less investment in renewable generation capacity, resulting in electricity with the greater dependence on non-renewable energy sources

4.3 Wider environmental concerns

Over the course of such large systematic changes (i.e. rapid low carbon transformations) as assessed in these pathways, it is crucial that wider environmental issues are monitored in order to avoid and limit other kinds of environmental damage. In this study, 17 other environmental impacts were therefore assessed in parallel with the climate change category to help inform decision-making. The environmental issues assessed range from Human toxicity, Freshwater Eutrophication to Land Occupation. The UK electricity sector for the year 2008 (the baseline year for the *transition pathways*) was compared to the sector in 2050 for all three pathways. This enabled the evaluation of changes in environmental impact due to the provision of electricity for the UK via alternative generator mixes. The environmental trade-offs between the three pathways in 2050 and 2008 are shown in Figure 5, in terms of percentage change of characterised LCA impacts against the 2008 system. Not all environmental impacts can be considered separately here (due to space restrictions), but the most significant results are discussed. However, the characterised results for all 18 environmental categories assessed for the three *Transition Pathways* are available in the supplementary information for year the 1990, and years 2008-2050 (see Table SI_4-6).

The focus here has been on the most significant changes in embodied impacts between the 2008 and 2050 electricity systems (or three *Transition Pathways*). The contributing factors to these impacts are discussed below. A positive percentage change suggests in Figure 5 an increased environmental impact over the 2008 electricity system, whilst a negative percentage change suggests an environmental benefit (or a reduction in impact).

Market Rules proved to be the most impactful *transition pathway* across the majority of impact categories (see Figure 5). The embodied impacts of the 2050 MR electricity system increased in 10 out of the 18 categories assessed when compared with 2008 levels. The TF *Transition Pathway* had the most associated environmental benefits, realising the greatest reduction in 13 categories out across all three pathways; only increasing impacts on the 2008 system for metal depletion, agricultural land occupation, and terrestrial ecotoxicity.

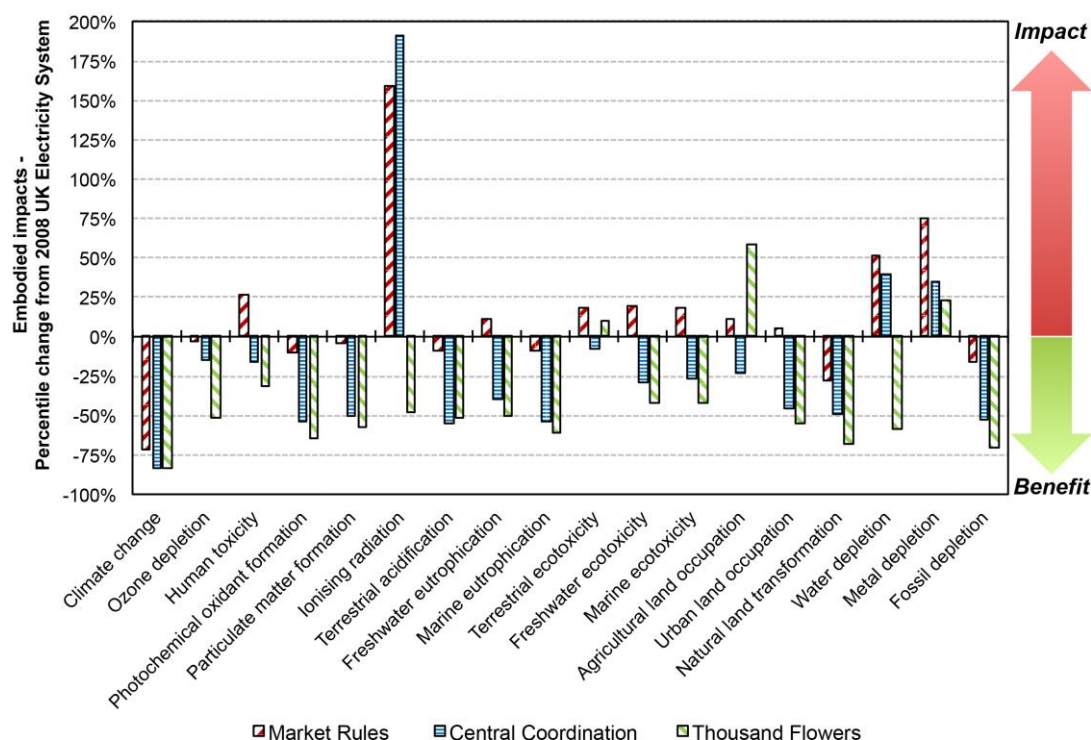


Figure 5. Variation in characterised embodied LCA impacts of the electricity sector for the three transition pathways; year 2050 compared to 2008.

Metal depletion was seen to rise for all three pathways which is discussed later in this section. The increased demand for biogas as CHP fuel was predominately accountable for the hike in both land occupation and terrestrial ecotoxicity, for which the biogas was partially derived from energy crops and other biomass resources. The TF pathway therefore saw a considerable increase in agricultural land occupation impacts, with an almost 60% increase over the 2008 power system. It expanded from 6.7×10^9 to 1.06×10^{10} m². The CC pathway experienced the lowest agricultural land occupation, falling to 5.17×10^9 m² by 2050; 23% lower than 2008 levels.

Although the CC pathways achieved the greatest decarbonisation, it did not reduce other environmental burdens at a similar rate, experiencing much lower environmental benefits than those provided by the TF pathway. The only categories, apart from climate change, where the CC pathways led to greater environmental benefits than its TF counterpart, were for terrestrial acidification, terrestrial ecotoxicity, and agricultural land occupation. This was due to the significant role of biogas-CHP in the TF pathway. The CC pathway had the highest impact out of all three pathways in terms of ionising radiation as a result of the large increase in nuclear power generation. This led to a large (191%) increase over 2008 levels, rising from 6.2×10^{10} kg U235eq to 1.8×10^{11} kg U235 eq.

Human toxicity, particulate matter formation, and photochemical oxidant formation impact assessment categories are all associated with increased human mortality³⁴. Only human toxicity

was seen to increase under the MR pathway: 27% higher than 2008 level, rising to 7.4×10^{10} kg 1,4-DB eq. In contrast, the TF pathway led to the lowest associated human toxicity; dropping 30% to 4×10^{10} kg 1,4-DB eq. The MR pathway only saw marginal reductions in particulate matter formation and photochemical oxidant formation, reducing by 4 and 10% respectively. Both the CC and TF pathways realised much better environmental benefits in these categories, with reductions of between 50-58% in particulate matter formation, and reductions of between 54-65% in photochemical oxidant formation.

Fossil fuel depletion fell below 2008 system levels for all three pathways by 2050. Despite achieving greater levels of decarbonisation, the MR pathway only experienced a 16% drop in Fossil fuel depletion (to 6.2×10^{10} kg oil eq by 2050), due to the high levels of coal and gas-fired generation (albeit with CCS). The TF pathway achieved the greatest reduction in fossil fuel depletion, decreasing by 70% on 2008 levels, to 2.2×10^{10} kg oil eq. In contrast, metal depletion was the only impact category where all three pathways displayed an increase on their 2008 system embodied impacts; rising by over 75% in the MR pathway, 35% in the CC pathway, and 23% under the TF pathway. Renewable energy technologies, such as solar PV, wave, tidal, and wind generation are all associated with high levels of metal depletion, and to a lesser extent nuclear generation. As the electricity system endeavours to decouple from fossil fuels, reliance on metal resources will steadily grow as the renewable energy sector develops.

5 Environmental consequences of UK energy policy shifts

The environmental consequences of UK energy policy shifts are presented in this section. The results are contrasted with the base reference case from Section 4, to investigate the environmental merits of enacting these energy policy shifts on the decarbonising UK electricity system.

5.1 Phase out of coal by 2025

The phase out of coal-fired power plants reduces GHG emissions associated with all three pathways; however, the MR pathway demonstrated the greatest benefit from this policy shift. Lifecycle GHG emissions were reduced by 31% for the MR pathway, 22% for the CC pathway, and only 12% for the TF pathway for the year 2050.

To investigate the full benefits of the coal phase out it is necessary to look at the GHG emissions curtailed over the course of the 2015-2050 transition. A total of 872.4 Mt CO₂e of life cycle GHG emissions are avoided through this phase out of coal under the MR pathway. This equates to 3.9 times the life cycle GHG emissions associated with the 2008 baseline system. In contrast, the phase out of coal under the TF pathways only avoided 294.5 Mt CO₂e of life cycle GHG emissions over the transition period; equating to 1.3 times life cycle GHG emissions of the 2008 system.

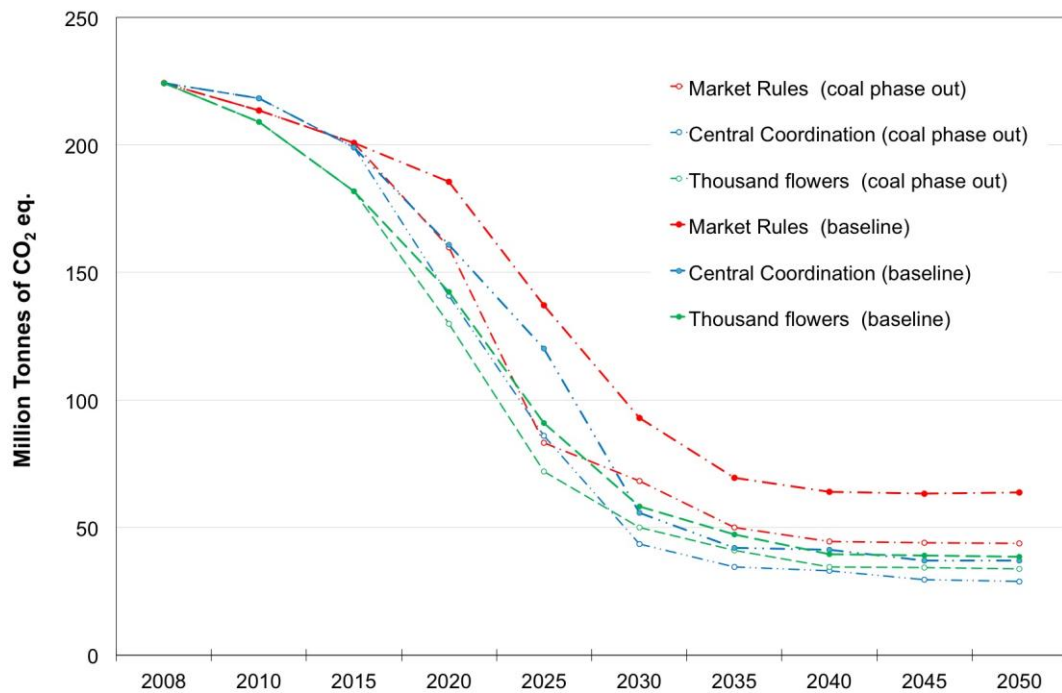


Figure 6. Total GHG emissions for the electricity sector (Mt CO₂e) 1990-2050 under the three *transition pathways* on a life cycle basis, compared to pathways with coal phase out.

The phase out of coal under the MR pathway avoided 441.3 Mt CO₂e direct GHG emissions; equivalent to 2.2 times the 2008 direct emissions. Whereas, the phase out of coal under the TF pathways only avoided 92.9 Mt CO₂e direct GHG emissions, which equates to just under half of the 2008 direct emissions.

A significant investment in new gas generation capacity will be required to replace the coal plants in such a phase out scenario. The system would be locked into a given level of emissions over the lifetime of the new gas-fired plants, which is typically around 35 years⁴⁷.

There was an additional 95 TWh of gas generation with CCS required in 2050 as a result of the coal phase out in MR. Primary demand for gas in 2050 would rise from 890 to 1700 PJ for the MR pathway (The petajoule (PJ) is equal to 10¹⁵ Joules), which is a rise from 1.1 times to almost 2.2 times the 2014 gas demand of the UK electricity system⁵.

Once again, the *Market Rules* pathway experiences the greatest environmental benefits from all three pathways due to the higher levels of coal generation and coal CCS present in this pathway. The percentage changes in total embodied impacts over the course of the three *Transition Pathways*, from the original pathways, have been presented in

Figure 7 in order to explore the implications of the coal phase out. The characterised results of the original *Transition Pathways*, along with results for the transitions with coal phase out have been included in Supplementary information (see Table SI_4-9).

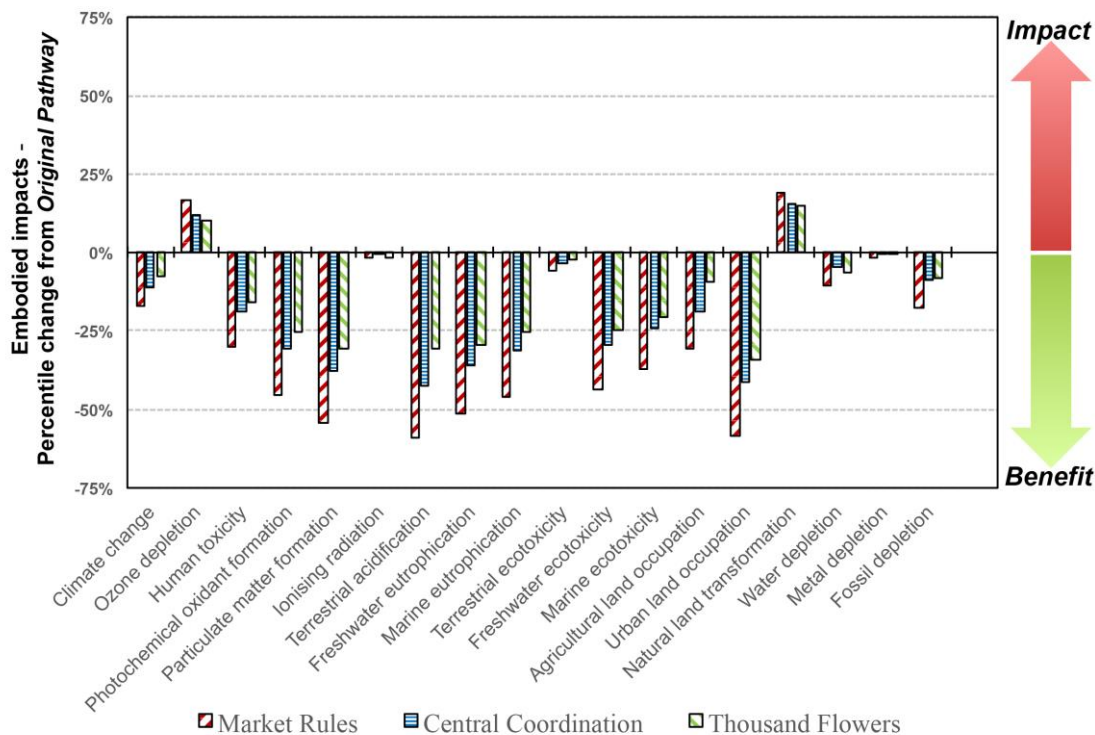


Figure 7. Variation in characterised embodied LCA impacts of the electricity sector from the original pathways, in response to the coal phase out, over the course of the three *transition pathways* from 2008-2050.

The majority of categories assessed (15 of the 18 categories) unsurprisingly demonstrated environmental benefits as a result of the coal phase out. A substantial reduction was seen in human toxicity, photochemical oxidant formation and particulate matter formation. These environmental impacts reduced by between 16-30%, 25-46%, and between 30-54% respectively; demonstrating that the phase out of coal will have far wider environmental benefits than the reduced GHG emissions alone. Two assessment categories showed a rise in impact, namely, ozone depletion and natural land transformation. Ozone depletion increased by between 10-16%, while natural land transformation rose by between 15-19%.

5.2 The future of CCS

The role of CCS in UK's energy future has been explored here in terms of both life cycle GHG emissions, and direct GHG emissions basis. Life cycle emissions have been investigated to explore the technology's full climate change mitigation potential, while direct emissions have been examined to explore the role of CCS in adhering to future UK climate change targets. The *Committee on Climate Change* (CCC) recommend UK carbon budgets (or interim targets) that will ultimately stretch out to 2050 based on territorial or 'production' GHG emissions within the country, and not 'consumption' emissions that incorporate those arising from (or embodied in) the importation of materials and products (e.g. from exporting countries, like China). This is because only production emissions make up the national targets embedded in the *Kyoto Protocol* (and its

likely 2020 successor). Total GHG emissions for the electricity sector from 2008 to 2050, under the three *Transition Pathways* with varying levels of CCS on a life cycle basis, are shown in Figure 8. The growth of CCS in the UK electricity sector has a much greater potential to mitigate GHG emissions than the phase out of coal from the electricity system. Contrasting the original pathway results, with that of the 0% CCS scenario, suggests that CCS could mitigate between 1105 and Mt 2639 CO₂e (where the higher figure relates to the MR pathway, whereas the lower figure is associated with the TF pathway) over the course of the transition on a life cycle basis.

Life cycle GHG emissions were seen to increase from 64 Mt CO₂e for the original *Market Rules* pathway to 167 Mt CO₂e for the MR power sector with 0% CCS in 2050; only attaining a 25% reduction on 2008 life cycle GHG emission levels. Direct emissions for the MR pathways in 2050 are seen to increase from 25 to 79 Mt CO₂e for 50% CCS, and to as high as 130 Mt CO₂e for 0% CCS. The reduction in direct emissions achieved by the MR pathway, on 1990 levels, would fall from 88% for the original pathway, to 63% for 50% CCS, and to as little as 40% for a pathway where no CCS is present. Evidently, the realisation of CCS is crucial to the decarbonisation of this pathway. Conversely, TF decarbonisation is only moderately impacted by the absence of CCS, with direct emissions rising from 7.2 to 22 Mt CO₂e for 50% CCS, and 38 Mt CO₂e for 0% CCS. This represents a drop in GHG reduction on 1990 levels from 97% for the original pathway, to 90% for 50% CCS, and 82% for 0% CCS.

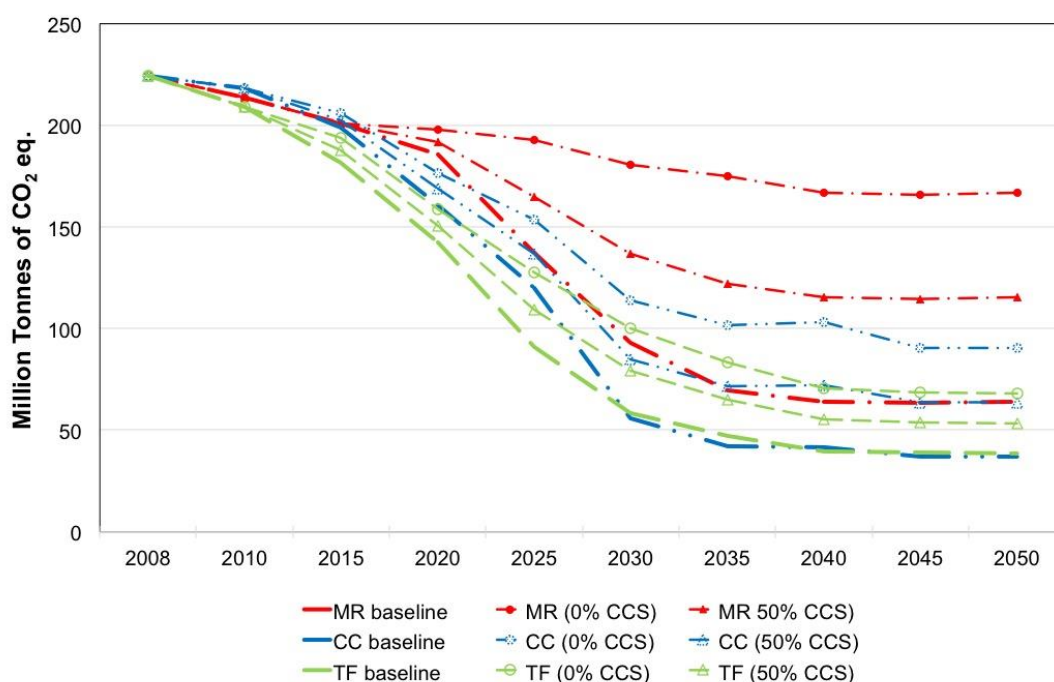


Figure 8. Total GHG emissions for the electricity sector (Mt CO₂e) 2008-2050 with varying levels of CCS under the three *transition pathways* on a life cycle basis.

The variation of CCS penetration in the UK electricity system for all three pathways has a much lower effect on *Cumulative Energy Demand* (CED) compared to life cycle emissions. The greatest reduction in energy demand occurred under the *Market Rules* pathway in response to the higher penetration of CCS under this pathway. CED dropped by 460 PJ in the MR pathway for 0% CCS case, representing an 8.7% reduction from the original pathway (v3.2). The *Thousand Flowers* pathway saw the smallest change in CED, only dropping by 67 PJ for 0% CCS, signifying a 6.7% drop from the CED of the original TF pathway.

5.3 Fuel type for combined heat and power and its allocation

Two version of the TF pathway were examined to evaluate the potential impact of CHP plants as a disruptive technology: one where all CHP was primarily fuelled by biogas, and another fuelled by biomass. Additionally, three allocation methods were employed to explore their impact on the environmental performance of CHP. The life cycle GHG emissions range from 27 to 45 Mt CO₂e in 2050 under the TF pathway, compared to the original (v3.2) pathway result of 38.6 Mt CO₂e. The TF pathway with biogas CHP, using the *exergy allocation* method had the highest associated GHG emissions, whilst TF pathway with biomass-fired CHP, using *energy allocation* had the lowest. Total system life cycle GHG emissions for the TF pathways, therefore, could be up to 30% less, or 17% greater than quantified in the original (v3.2) pathway depending on these considerations.

Furthermore, the use of biomass or biogas to fuel CHP could lead to shifts in the wider environmental performance of the electricity system. Although the 2050 TF pathway electricity system with biogas-fired CHP was shown to emit greater GHG emissions than the system with biomass-fired CHP, it had lower associated environmental impacts over a wide variety of impact categories. Assessing systems using DUKES allocation, human toxicity was lower by 2.8×10^{10} kg 1,4-DB eq., photochemical oxidant formation lower by 4.1×10^7 kg NMVOC, and particular matter formation lower by 3.9×10^6 kg PM10 eq. (68%, 26% and 4% lower respectively from the system with biomass-CHP). The 2050 TF pathway electricity system with biogas-fired CHP also demonstrated considerably lower terrestrial ecotoxicity and agricultural land occupation, as well as slightly lower 'urban land occupation'. However, there was much higher associated terrestrial acidification and also increased associated ozone depletion. [Full life cycle impact assessment results for each 2050 TF pathway system explored can be found in Table SI_ 10]

6 Concluding Remarks

A series of energy policy shifts have been recently announced by the UK Government signifying a new direction, or 'reset', for energy policy^{10, 11}. This paper represents the first attempt of evaluating the environmental consequences of these policies for the future UK electricity system. Furthermore, the environmental consequences of a potential policy shift relating to bioenergy supply chains were also investigated. The impacts of these policy shifts were explored employing

three *transition pathways* to a more electric low carbon future, which were developed to meet the 2050 UK climate change targets. Both environmental life cycle assessment (LCA) and energy analysis were applied in parallel from ‘cradle-to-gate’ to evaluate the consequences on the performance of the future UK electricity sector.

The three reference pathways (before potential policy changes) were all seen to decarbonise sufficiently to contribute to the statutory target of 80% reduction on direct GHG emissions across the UK economy against 1990 levels. The most decentralised *Thousand Flowers* (TF) pathway has the lowest GHG emissions on a direct basis; experiencing a 97% reduction on 1990 levels compared to 88% for the *Market Rules* (MR) pathway, and 93% for the *Central Coordination* (CC) pathway. Nonetheless, no pathway succeeds in completely eliminating emissions by 2050 as advocated by the CCC⁹. All the pathways demonstrated much lower reductions on a life cycle basis, as a result of their upstream emissions, some of which occur outside the national border and are thereby excluded from UK carbon budgets²². The MR pathway only achieves a 75% GHG reduction compared to 1990 emissions levels on a life cycle basis, whereas the CC and TF pathways both achieve around an 85% reduction in GHG emissions. Furthermore, the CC pathway proved to have the lowest life cycle GHG emissions by 2050. The difference between the direct and life cycle GHG performances of the three pathways, demonstrate the importance of considering the whole system in order to avoid unaccounted negative effects upstream.

The application of LCA to the pathways highlighted an increase in some environmental burdens across all three pathways compared to the 2008 baseline system. Hence, the decarbonisation of the electricity sector will have to be balanced across the spectrum of environmental issues in order to limit wider environmental damage. As the electricity system endeavours to decouple from fossil fuels, and their associated high GHG emissions, regardless of the pathway, reliance on metal resources will steadily grow as the renewable energy sector develops. For all three pathways, metal depletion increased significantly in terms of 2008 embodied impacts, rising by 75% for the MR pathway, 35% for the CC pathway and 23% for the TF pathway. Despite the CC pathway having the lowest life cycle GHG emissions, its TF counterpart had the largest associated environmental benefits of all the pathways, realising the greatest reduction in 13 out of 18 impact categories. Additionally, the TF pathway was the only one to decouple its Cumulative Energy Demand (CED) from overall electricity demand as a consequence of the large reduction in non-renewable energy use. Globally, GHG emissions have become the central focus in the fight against climate change. These results demonstrate the importance of a fuller consideration of wider environmental concerns, and not just GHG emissions alone.

A key focus of this research was to examine the recent policy shift to eliminate coal generation (the most GHG polluting generator, and presently 30% of the generation mix) in an effort to decarbonise the electricity sector^{5, 10}. This research investigates the effectiveness of this decarbonising strategy, and also the wider environmental implications that may result from the

removal of such a dominant technology. GHG emissions did indeed decrease with diminishing coal generation, but at varying rates depending on the *Transition Pathway* concerned. However, such a move could affect UK security of supply by inducing a significant higher demand of gas even with the possible development of a UK shale gas industry over the medium to longer-term. Gas demand for electricity was seen to rise by up to a factor of 2.2 over current levels by 2050 in the MR pathway. Financial difficulties in securing new nuclear power plants in the UK ⁴³ are likely to exacerbate this issue. The phase out of coal generation could mitigate between 294.5 and 872.4 Mt CO₂e of GHG emissions on a life cycle basis over the course of the transition period to 2050: a reduction of between 7-16% in life cycle GHG emissions, where the larger figures are associated with the MR pathway and the lower figures are associated with the TF pathway. On a direct emissions basis, between 92.9 and 441.3 Mt CO₂e of GHG emissions could be mitigated (a reduction of between 4-11% direct GHG emissions). The coal phase out was seen to have significant environmental benefits across a wide spectrum of burdens; with 15 out of 18 impact categories exhibiting improvements.

With the government recently withdrawing support and funding into carbon capture and storage ¹² development, this paper attempts to measure the significance of our continued use of GHG generators without carbon abatement strategies. A significant finding is that the adoption of CCS in the UK has much greater potential to mitigate GHG emissions than the early phase out of coal across all pathways. The TF pathway was the only one that secured sufficient decarbonisation (on a direct, operational or 'stack' basis) in the absence of CCS to potentially adhere to UK carbon budgets. Direct emissions reduction was seen to fall from 97% against the original pathway on 1990 levels to 82% for the pathway with no CCS incorporated. Nevertheless, all sectors across the economy would need to reach the same level of decarbonisation without carbon capture (i.e., the 2050 80% reduction on 1990 GHG emissions levels). According to the CCC ⁹, such a future could double the cost of reaching the UK carbon target. In the absence of CCS, the UK electricity sector must quickly reduce its reliance on both coal and natural gas to a minimum, and also secure large advancements in energy demand reduction in line with the TF pathway.

This work explores the adoption of bioenergy to displace fossil fuels in order to obtain a deeper decarbonisation in the electricity sector. The exact policy decisions to lead this transition are a matter of wider debate. Two different bioenergy pathways, biomass and biogas CHP, are compared in order to help inform these decisions. Both generation types are touted as likely technologies for the exploitation of bioenergy. Results indicate that although GHG emissions associated with biomass were lower than biogas fuelled CHP, it gave rise to greater environmental burdens across other assessed impact categories. The variation in bio-feedstocks was shown to have a significant impact on the life cycle GHG emissions. Additionally, lifecycle impacts were seen to vary considerable between allocation methods. A standard allocation procedure needs to be selected when informing policy to provide clarity; a matter which requires attention. Although both forms

of generations are considered ‘carbon neutral’ (where the uptake in carbon during cultivation balances the bioenergy direct emissions, considered effectively zero under direct carbon accounting practices), the life cycle emissions were seen to vary considerably; ranging between 30% less or 17% greater than the original (v3.2) pathway in 2050. As the electricity system continues to decarbonise, these GHG emissions from the bioenergy supply chains may become increasingly influential, as seen here in the TF pathway, effectively locking the system to a potentially higher level of emissions. An increased demand for bioenergy supply will inevitably result in various environmental trade-offs, these will be largely dependent on specific choices taken, and as highlighted in this work, which must be assessed comprehensively.

This study quantifies the wide range of environmental consequences that are likely to result from policy shifts – some in the recent UK energy policy ‘reset’ - on future UK low carbon electricity systems. This work illustrates the guiding principles of LCA as a valuable tool to measure the effects of proposed policy decisions, and in the case of bioenergy choices as a proactive tool in the shaping of new policy choices ahead. The shifting energy policies had different impacts depending on the future pathway and disruptive technologies examined, but indicated that environmental trade-offs were unavoidable. The value of any new policy direction must be evaluated not only against medium-term climate change goals, but against long-term, system-wide goals over a wide spectrum of environmental metrics.

Nomenclature

CC	Central Coordination
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CED	Cumulative Energy Demand
CHP	Combined heat and power
DECC	Department of Energy and Climate Change
DUKES	Digest of United Kingdom Energy Statistics
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	International Panel on Climate Change
MR	Market Rules
NGO	Non-governmental organization
NRE	Non-renewable Energy
TF	Thousand Flowers
UK	United Kingdom

Acknowledgements

This work is part of a programme of research at the University of Bath on the technology assessment of low carbon energy systems and *transition pathways* that is supported by a series of UK research grants and contracts awarded by various bodies. In the present context, Professor Hammond is jointly leading a large consortium of university partners funded by the UK *Engineering and Physical Sciences Research Council* (EPSRC) entitled '*Realising Transition Pathways: Whole Systems Analysis for a UK More Electric Low Carbon Energy Future*' [under Grant EP/F022832/1]. Áine O' Grady is wholly funded via this grant. Both authors are grateful for the interaction with other members of the Consortium (and its predecessor) made up of participants from nine UK universities. However, the views expressed here are those of the authors alone, and do not necessarily reflect the views of the collaborators or the policies of the funding body.

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10.6 Key Outputs

The environmental consequences of recent shifts in UK energy policy on the future UK electricity system are evaluated in this paper. Firstly, the life cycle energy and environmental impacts associated with the latest iteration of the Transition pathways (version 3.2) was determined; thereby fulfilling objective 2 of the thesis. The *Market Rules* pathway experienced the least decarbonisation on a life cycle basis of all three pathways in 2050, reaching a 75% GHG reduction compared to 1990 emissions levels. The *Central Coordination* and *Thousand Flowers* pathways both achieve around an 85% reduction in GHG emissions, with *Central Coordination* proving to be the most decarbonised pathway on a life cycle basis. However, *Thousand Flowers* had the largest associated environmental benefits of all the pathways, realising the greatest reduction in 13 out of 18 impact categories. Additionally, the TF pathway was the only one to decouple its *Cumulative Energy Demand* (CED) from overall electricity demand as a consequence of the large reduction in non-renewable energy use. These results demonstrate the importance of a full consideration of wider environmental concerns, and not just GHG emissions alone.

The energy policy shifts had different impacts depending on the future pathway and disruptive technologies examined, but indicated that environmental trade-offs were unavoidable. The impact of these energy policy shifts were compared with the reference case to quantify the impact of these systemic changes on the environmental performance of the UK electricity sector, fulfilling objective 6 of this thesis. The phase out of coal generation could potentially mitigate between 294.5 and 872.4 Mt CO₂e of GHG emissions, on a life cycle basis, over the course of the transition period to 2050. This equates to a fall of between 12-31% in life cycle GHG emissions from the reference case (depending on the pathway). The coal phase out was seen to have significant environmental benefits across a wide spectrum of burdens; with 15 out of 18 impact categories exhibiting improvements. However, gas demand was seen to more than double current levels in response to the shift from coal to gas.

The growth of CCS in the UK has a much greater potential to mitigate GHG emissions than the early phase out of coal across all pathways. The use of CCS in the *transition pathways* could mitigate between 1,105 and 2,639 Mt CO₂e over the course of the transition period to 2050. Only TF pathway reached sufficient decarbonisation in the absence of CCS; however, again this pathway represents the greatest departure from the current system.

The life cycle GHG emissions of the *Thousand Flowers* pathway were heavily dependent on both the fuel type used for CHP, and also the allocation method applied. Although direct emissions would remain constant, life cycle GHG emissions were seen to vary considerably based on these parameters, ranging between 30% less or 17% greater than the original (v3.2) pathway in 2050. Despite lower associated GHG emissions with biomass-CHP, it gave rise to greater associated environmental burdens than biogas-fuelled CHP for a wide variety of other impact categories assessed.

11 Conclusions

Developed Nations are implementing measures to transform their energy systems in an effort to mitigate climate change [14, 15]. Decarbonisation of their electricity systems has been adopted as a principal strategy in driving this required transformation [96]. Nevertheless, due to the complexities involved, no consensus has been reached on the optimum route to deliver this fundamental goal. Most critically, electrification of other sectors such as heat and transport, supplied by a low carbon electricity supply, is considered one of the prime means of achieving greater economy-wide carbon reductions [26, 48, 102]. If electricity is set to play a central role in the global fight against climate change, it's critical that implemented decarbonisation policies are confirmed to deliver an electricity source which is 'truly' low carbon. Furthermore, the wider environmental impacts resulting from this large systemic change must also be evaluated, to ensure that other issues are avoided.

This thesis develops an evidence base to help direct future decision-making in not only maximising the carbon reduction potential of future electricity systems, but also limiting their wider environmental damage. The environmental management tool Life Cycle Assessment (LCA) was used, as the means of assessing the environmental implications of a transforming electricity system in response to different decarbonisation approaches. This issue was examined in a UK context, investigating three potential low carbon transitions for the UK's electricity system out to 2050, known as the *Transition Pathways* (see section 1.4). This holistic methodology ensures that the 'true' environmental impacts associated with these future electricity systems were fully quantified.

In the current policy landscape, the environmental merits of different forms of electricity generation are primarily judged by their direct GHG performance (i.e. direct or stack emissions). This thesis highlights the environmental significance of upstream emissions, setting it apart from analysis conducted by the Committee on Climate Change (CCC) and Department of Energy and Climate Change (DECC), which do not fully account for these wider emissions. Additionally, it evaluates the wider energy and environmental implications of a transitioning electricity system, demonstrating that environmental trade-offs are unavoidable. A greater understanding of the intricacies and dynamics of future electricity systems is provided. The collective findings provide clear scientific guidance to help frame future decarbonisation policies to minimise the environmental consequences of the future electricity sector.

11.1 Fulfilling the Objectives of this Thesis

The primary aim of the work reported in this thesis was:

To assess the energy and environmental impacts of the UK electricity system, and its associated technologies, as it transitions towards a low carbon future.

The aim was met by fulfilling seven objectives as detailed in Section 1.7. The following sections outline how these objectives were accomplished through the presented portfolio of research articles, along with their main outputs and findings.

11.1.1 To perform a critical review of the life cycle assessment methodology as applied to the evaluation of energy systems

A series of energy sector case studies were examined demonstrating the usefulness of LCA for assessing energy systems. An in-depth assessment of its strengths and weaknesses distinguished the best use of the methodology and its findings, especially relevant for energy practitioners and policy analysts.

Main findings

- LCA provides a holistic environmental appraisal of an energy system, assessing a wide range of predetermined environmental categories. Nonetheless, it's not suitable for determining local impacts. It was asserted to be a suitable approach for supporting proactive decision-making; however, it doesn't quantify actual environmental damage, but rather the potential environmental implications.
- LCA was found to be a very powerful tool for pinpointing environmental hotspots within large systems. It's most effective at comparing two energy systems, rather than reporting on one individual system. Procedural transparency and alignment of methodology choices are critical in order to ensure a fair comparison.
- Peer-reviewed data based on a generic system are often used to limit uncertainties. Hence, findings from assessments thereby only reflect that of a typical energy system, and do not consider any site-specific or temporal factors. Nonetheless, LCA findings were found to be a robust quantitative basis to inform policy, but would not be suitable to guide site based environmental management.

11.1.2 To determine the life cycle energy, greenhouse gas (GHG) and environmental impacts of the development of a more electric UK power sector.

A primary focus of this thesis was to establish the 'true' life cycle environmental performance of the future UK electricity sector in response to decarbonisation policies. Three potential low carbon transitions for the UK's electricity system (known as the *Transition Pathways*) were evaluated using LCA. All three pathways achieved significant decarbonisation, however, no pathway succeeded in completely eliminating emissions by 2050 as advocated by the CCC [21]. The remaining emissions reported in 2050 were largely the result of upstream emissions, some of which occur outside the national border and are thereby excluded from current UK carbon budgets [53].

The *Market Rules* (MR) pathway experienced the least decarbonisation by 2050 largely due to heavy dependence on coal and gas carbon capture, which both have high associated upstream

emissions. MR achieves a 75% GHG reduction compared to 1990 emissions levels on a life cycle basis, whereas both the *Central Coordination* (CC) and *Thousand Flowers* (TF) pathways achieve around 85% reduction in emissions on the same basis. The CC delivered the greatest decarbonisation, closely followed by the TF pathways.

The TF pathway achieved similar decarbonisation as the CC pathway over the total system, despite having significantly higher associated emissions per unit of electricity. These results demonstrate the significant role of demand reduction in lowering life cycle GHG emissions regardless of the performance of the technologies installed.

Wider energy and environmental implications of a transforming electricity sector in response to decarbonisation policies were also determined. The main outputs of this work are as follows:

- LCA application to the pathways highlighted an increase in some environmental burdens across all three pathways compared to the 2008 baseline system, suggesting that environmental trade-offs were unavoidable. Hence, the decarbonisation of the electricity sector will have to be balanced across the spectrum of environmental issues in order to limit wider environmental damage.
- The MR pathway proved to be the most impactful *Transition Pathway* across the majority of the impact categories assessed. The embodied impacts of the 2050 MR electricity system increased in 10 out of the 18 categories assessed compared with 2008 levels. The TF pathway had the most associated environmental benefits, realising the greatest reduction in 13 categories across all three pathways over the same period.
- Largely reflecting trends in electricity demand, the Cumulative Energy Demand was seen to increase for both the MR and CC pathways compared to 2008 baseline levels. Only TF decouple its CED from overall electricity demand, proving to be the only pathway to truly release the electricity sector from its heavy reliance on non-renewable energy use.
- Reliance on metal resources was seen to steadily grow for all three pathways as the renewable energy sector develops and displaces fossil-fuelled generators. These results demonstrate the importance of a fuller consideration of wider environmental concerns, and not just GHG emissions alone.

11.1.3 To highlight the environmental significance of 'upstream emissions', along with their technological and policy implications.

The research conducted in this thesis highlighted a major issue in using electrification as a primary means of achieving decarbonisation across the economy. These policies could potentially result in the adoption of activities that have significant associated upstream GHG emissions, which are not fully accounted for under the current regime. If upstream emissions were adequately accounted for, large increases may be seen in the GHG performance of all products and services consuming electricity across the economy. Nonetheless, GHG reduction targets will still appear to be met

under current legislation. The collective efforts driven by policies to meet these ambitious targets could therefore, in fact, deliver less meaningful change in the fight against global warming.

This research affirmed the importance of considering the whole system, including upstream emissions, and incorporating life cycle thinking in policy-making. The environmental significance of upstream emissions associated with the electricity sector was highlighted in both article I and VII of this thesis. The difference between the direct and complete life cycle GHG performances of the three pathways demonstrates the risk posed by unaccounted negative effects upstream.

These upstream emissions are widely viewed as static, and a minor contribution to the overall life cycle emissions associated with the electricity sector, by energy policymakers. This research suggests that this is a misleading viewpoint. Research in this thesis has not only shown the growing importance of these emissions as this sector decarbonises, but also explored the potential dynamics of these emissions in response to transforming supply chains (see article VI).

11.1.4 To explore how multidisciplinary and interdisciplinary modelling approaches can inform the future development of the UK power system within a decarbonisation framework.

The *Realising Transition Pathways* [101] consortium was established to analyse the technical feasibility, social acceptability and environmental and economic implications of a transitioning electricity system. This interdisciplinary approach could allow in-depth cross-cutting insights to be developed, providing a full assessment of the advantages and disadvantages associated with these highly electrified energy futures.

The elaboration of these socio-technical scenarios proved critical in providing a unified platform, to allow over-arching insights to be deduced more readily across multiple disciplines. Hence, a significant effort was taken to enhance and refine the elaboration of these pathways. The more consistent and unified these pathways become, the closer they represented the transition of the electricity system in reality. This would greatly increase their dependability and credibility, and thereby better equip them to inform future decision-making for this sector.

The combined use of quantitative models and qualitative storylines is widely employed for the elaboration of energy scenarios in order to facilitate the investigation of the future systems [98-100]. Despite the wide application of storylines and models, little research had been conducted on best methodological approaches to linking both methods, or indeed facilitating their greater integration. Multidisciplinary and interdisciplinary modelling approaches were developed by members of the RTP consortium (including the candidate) in Article III and IV to facilitate this process. These methods led to a greater understanding of the future development of the UK power system within a decarbonisation framework.

This methodology could offer guidance to the number of growing interdisciplinary projects worldwide, which bring social scientists and energy modellers together, to facilitate interdisciplinary research, and to build more robust future scenarios.

11.1.5 To examine the environmental impacts of new entrant electricity generators options which may be adopted, and their role in the decarbonisation of the UK electricity sector.

A low carbon transition will require the adoption of new electricity generators to achieve the ambitious targets. The introduction of a new electricity generator comes with a unique set of environmental impacts which must be quantified and managed. This thesis examines the role of the following new entrant generators in the decarbonisation of the UK electricity sector:

- Gas-fired generation fuelled by shale gas;
- Gas-fired generation fuelled by biomethane;
- Wave;
- Tidal;
- Fossil-fuelled generation with carbon capture and storage (CCS).

The adoption of shale gas in the UK could fundamentally re-order the Nation's energy policies, and alter the direction of the future energy system. The environmental impact of this new entrant energy source was investigated in Article VI, along with the economic, safety and social repercussions in the context of the future UK energy system. It was determined that many of the environmental issues could be completely circumvented, or greatly reduced, by sanctioning the following measures:

- baseline monitoring of air, land and water, and independent monitoring of seismic activity before and during operation;
- abstraction of water in line with current UK licensing process;
- careful management of wastewater;
- properly design wells with guaranteed high well integrity;
- disposal of flowback fluid in line with current regulation, and the
- adoption of 'green completions'.

Nevertheless, even with the most stringent regulatory system in place, issues such as faulty wells, leaks and spillage events are expected to occur, as they are common in all oil and gas well activities. A regulatory system is only as strong as its enforcement, strengthened by tough deterrent penalties.

Associated GHG emissions for shale gas were on average, significantly lower than its liquefied natural gas (LNG) and Russian gas counterparts. However, this research concludes that shale gas could support a UK low carbon transition but must be heavily managed, and impeded from

becoming a dominant contributor. Failure to do so poses the risk of infringing on carbon budgets. An over reliance on gas-fired generation could lead to high GHG emissions lock-in over the course of the gas plant's life.

Even moderate levels of biomethane in the gas supply were demonstrated to play a vital role in limiting the GHG emissions from future gas-fired generation. The carbon credits associated with biomethane proved essential in offsetting rising upstream emissions in response to the gas supply transformation. Furthermore, disadvantaged by the lowest penetration of biomethane, the high shale gas supply scenario resulted in the highest associated lifecycle GHG emissions for the electricity sector.

The environmental impacts associated with other new entrant electricity generators were also investigated over the course of this thesis. Wave and tidal generation, and fossil-fuelled generation with CCS were incorporated in the assessment of the electricity sector transitions. However, limited data were available to truly assess these technologies due to their immaturity. The gathering of quality LCA data is critical for these novel technologies, as they advance from demonstration stage to full-scale deployment. Once more data becomes available, it will facilitate more informed assessments of entrant technologies' potential to decarbonisation of the electricity sector to be performed.

11.1.6 To identify areas of considerable systemic change for the future UK power system, and quantify their impact on the environmental performance of future UK electricity.

The future of the UK electricity sector remains relatively undetermined, and is therefore subject to significant systemic change that was not considered in the earlier assessment of the *Transitions Pathways*. Key areas identified in this thesis were:

- The potential gas supply evolution transformation expected as domestic natural gas supply diminishes,
- Recent energy policy shifts, which could see an early phase out of coal by 2025, and the withdrawal of funding to enable CCS to reach commercialisation
- Potential policy shift, such as, the support for different bioenergy supply pathways.

The three *Transition Pathways* were used to explore the impact of the resulting systemic change on the environmental performance of future UK electricity in Article VI, and Article VII.

Gas supply evolution

Gas generation is widely seen as a critical 'bridging' technology to facilitate the transition to a low carbon electricity source. This thesis recognises that gas sources are set to undergo a significant transition in the United Kingdom (UK), which will alter the associated environmental impacts of power generation. This potential gas supply transition was investigated in Article VI to quantify its potential ramification for the environmental performance of the UK electricity sector. Main insights and findings of this research were;

- Life cycle GHG emissions of the UK electricity sector were seen to increase compared to the baseline, unless the penetration of biomethane within the gas supply is sufficient to negate the rising upstream emissions.
- The direct GHG intensity of UK electricity (its perceived performance) appeared lower for all three pathways than the baseline, as a result of the carbon credit afforded by the influx of biomethane (particularly when combined with CCS). However, the total life cycle emissions of the UK electricity sector (its real performance) were seen to rise for the future supply mixes examined. Hence, the electricity will appear ‘lower carbon’, despite the actual total GHG emissions increasing in response to the gas supply transformation. These results further stress the importance of considering the comprehensive total life cycle GHG impacts of electricity generation when developing and implementing new decarbonisation policies, rather than direct fossil emissions alone.
- CCS proved in this research to be a critical element of a low carbon transition with gas-fired generation poised as a ‘bridging’ technology. Gas generation should not be widely considered in any transition of the electricity sector in the absence of fully operational CCS technology.

Coal phase out and CCS support

The potential environmental consequences of an early phase out of coal generation by 2025 were investigated in Article VII. The following implications were deduced from the removal of such a dominant technology:

- This systemic change delivered moderate levels of increased decarbonisation, but at varying degrees depending on the transition pathway assessed.
- Such a swift transition could induce significant increased demand for gas, with the potential for as much as a two fold increase from current levels by 2050. This could bring some security of supply issues to the fore, even in the event of a UK shale gas revolution. Nonetheless, this considerable systemic change could deliver significant environmental benefits across a wide spectrum of burdens; with 15 out of 18 impact categories assessed exhibiting improvements from baseline pathways.
- In order for supply to satisfy demand, it could lead to greater investment in additional new gas capacity in the near term, again, locking the system into a certain level of emissions. Since this research suggests that only moderate increase in decarbonisation is achieved through the early phase out of coal, it is important that this policy goal is balanced with achieving the overall carbon reduction required to meet carbon budgets.

- The development of CCS in the UK has a much greater potential to mitigate GHG emissions than the early phase out of coal across all pathways. In fact, only the TF pathway reached sufficient decarbonisation in the absence of CCS that could potentially adhere to the UK carbon budgets. Interestingly, this pathway represents the greater transformation from the current system.

Bioenergy supply pathways

Deeper decarbonisation of the electricity sector is likely to be achieved with the greater adoption of bioenergy. The extent to which this energy source can contribute to the wider energy sector is still being deliberated upon, and could have large ramifications on environmental performance of the future UK electricity. Two different bioenergy pathways, biomass and biogas CHP, were compared in Article VII in order to help contribute to this ongoing debate. The following was concluded based on the assessment of their potential contribution to the transition pathways:

- As the electricity system becomes increasingly decarbonised the GHG emissions associated with the bioenergy supply chains may become increasingly influential (as seen in the TF pathway), potentially limiting the longer-term low carbon potential of UK electricity. In contrast, the CC pathway delivered an electricity supply with much lower associated GHG emissions per kWh basis by 2050, with more modest penetration of this technology.
- These higher emissions, combined with potential constraints on future bioenergy supply, would suggest that bio-fuelled CHP should not be relied upon as a dominant electricity generation technology. However, this technology has the capability to contribute to network balancing duties, and also the decarbonisation of the heat sector; two major challenges which must be addressed by any low carbon transition. Hence, this technology should be supported in the UK but at moderate levels in line with addressing these wider issues.

11.2 Novel Contribution of this Thesis

Key UK energy policy drivers are to deliver a low carbon (on a ‘direct’ basis), affordable and secure energy supply. However, current policies in place to direct the future of the electricity system do not adequately account for any non-direct GHG emissions, or other wider environmental impacts. The portfolio of research presented in this thesis provides scientific evidence to inform proactive decision-making by policymakers and other energy stakeholders on these wider energy and environmental impacts. This thesis contributes to a better understanding of the implications of a transforming electricity system in response to different decarbonisation approaches. The breadth of research, across seven related articles is framed to facilitate greater appreciation of the wider environmental impacts associated with the transition to different future UK electricity systems, and the adoption of their associated technologies.

Many novel author-led research articles were developed to provide the ‘environmental’ component of the wider sustainability appraisal (assessing the technical, environmental, economic and social implications) of the alternative transition pathways to a UK low carbon electricity future. The presented results have received academic recognition in presenting peer-reviewed technical accounts of a transitioning electricity system. Moreover, this work has a much wider societal impact, providing greater understanding to a wider readership concerned with the environmental impacts of energy systems, and the conflicts, compromises and restrictions that face a nation attempting to decarbonize whilst still ‘keeping the lights on’.

Seven peer-reviewed articles, consisting of book chapter and journal publications, are presented in this thesis. Each provides academic depth and/or breadth in the understanding of the environmental impact of a transitioning electricity system. An overview of the research contribution of this thesis is provided in Figure 9. The full findings and details can be found elsewhere in this thesis; however the novelty and impact of the work can be appreciated as follows:

Articles:

- I This book chapter presents the strengths and weaknesses of the LCA methodology when used to evaluate energy systems. The chapter has immediate impact on research areas and policy decisions concerned with understanding the impacts of an entire energy system and require factual and contextual accounts of the LCA tool. It is framed to be relevant to wider energy stakeholders and policy makers, and those both familiar and unfamiliar with LCA.
- II This article identified a critical policy failure when accounting for the climate change impacts of electricity generation. This proved particularly significant given the potential role of electricity as a low carbon energy source for wider decarbonisation strategies. This analysis highlighted the need to account for upstream emissions within the power sector, which have not been fully reported by the governing bodies [Committee on Climate

Change (CCC) and the Department of Energy and Climate Change (DECC)]. The results of this work acted as a baseline for further research into future gas supply dynamics(see Article VI) The LCA data generated in this research also increase the robustness of LCA carried out on products and services in to the future (as incorporated into the life cycle inventory (LCI) of Rogers et al. examination of net carbon homes [103]. Access to these datasets is critical to help guide successful decarbonisation strategies beyond the electricity sector. The wider impact of this work is the better consideration of life cycle GHG impacts of electricity generation by policy-makers when devising new policy measures.

- III Methods to better link qualitative and quantitative scenario approaches were developed to enhance scenario development in this article. A novel ‘landscape of models’ approach was developed and is presented here, covering the input from consortium members with different backgrounds in the energy sector; various technical, policy, social and economic. The harmonising of these actor standpoints, system boundaries and assumptions has allowed for a rigorous interrogation of scenarios. The impact of such work is both immediate in terms of having a robust scenario set for the transitioning energy system models, but also has wider implications and benefits to other multi-disciplinary teams involved in scenario modelling.
- IV A new approach to scenario development is presented in this article which fully reconciles qualitative storylines and their quantitative representation through a structured interdisciplinary methodology. This research has significant scope for impact through providing guidance to build more robust future scenarios, not only for socio-technical storylines, but also further afield for the quantification of any qualitative storyline.
- V This article provides an unbiased assessment and review of the current thinking of the economic, environmental, safety and social repercussions of shale gas extraction in the UK. Such an appraisal conducted with high academic rigour, free of advocacy, is a vital contribution to the national dialogue, in the face of the adoption of this contentious technology. The evidence presented and contrasted in this article has far reaching impact through informing a wide range of stakeholders, and the wider public of the most noteworthy implications of this technology.
- VI The ramifications of an evolving gas supply on the GHG performance of the future UK electricity system was first investigated in this article. The long-term impact of evolving gas supply GHG emissions, has not been greatly considered, being largely ignored and treated as ‘inconsequential’ by governmental bodies. The analysis presented in this article suggests that an evolving gas supply could have a significant bearing on the GHG performance of the future UK electricity system. Recommendations outlined in this article equip policy-makers with vital insights to limit the impact of rising gas supply GHG emissions.

VII The first assessment of long-term environmental repercussions arising from significant policy shifts (enacted and discussed during the 2015-2016 period), concerning the UK electricity system, is presented in this journal. The merits of enacting such policies from a decarbonisation perspective were contrasted with wider environmental trade-offs. This research provided the final environmental assessment of three transition pathways, to contribute to the wider-arching sustainability appraisal of these UK power system transitions. Wider impact of this work would be the adoption of deduced policy recommendations, to not only improves decarbonisation policies, but also to limit resulting wider unavoidable environmental repercussions.

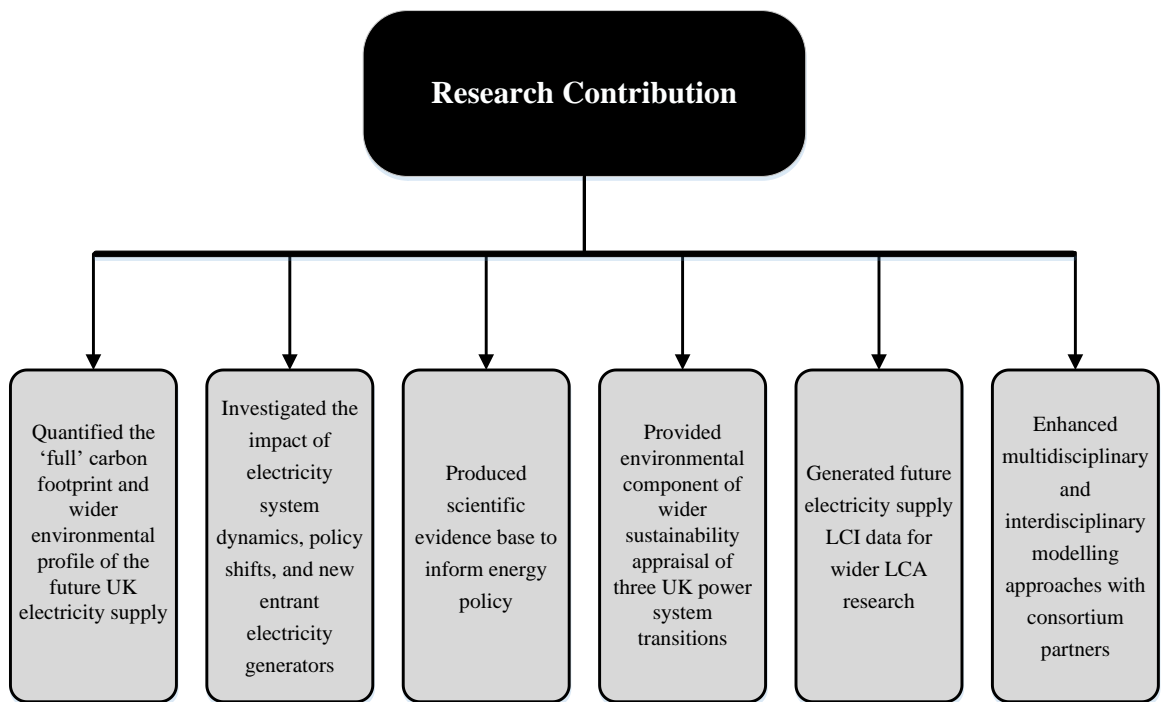


Figure 9. Research Contribution Overview

11.3 Recommendations

A wide evidence base was developed within this portfolio of research, which could help guide strategies and support decision-making regarding transitioning electricity systems. The following recommendations have been drawn from the outputs of this thesis:

- The current system is already lagging behind the trajectory of the pathways developed in this research, which as they stood represented a very ambitious scale-up of clean technologies. Stronger and more long-term policy action is now required if a transition of this nature is to be achieved within the timeframe.
- This research affirms that lifecycle thinking must be better incorporated in policy development, particularly accounting for life cycle GHG emissions when developing and implementing new decarbonisation policies. Moreover, the value of new policy direction needs to be evaluated not just against medium term goals (as evident from recent energy policy announcements), but also against long-term, system wide goals over a wide spectrum of environmental metrics.
- More emphasis on the importance of accounting for both present and future upstream emissions is required. Future supply chain dynamics and their emissions were shown to have significant bearing on the GHG performance of future UK electricity.
- Environmental compromises were unavoidable for all decarbonisation approaches assessed. The decarbonisation of the electricity sector will have to be balanced across a wide spectrum of environmental issues in order to limit wider environmental damage.
- Regardless of the clean technology generation mix established, it cannot achieve the level of decarbonisation necessary alone. Reduced demand proved fundamental to each pathway's success. Large improvements in energy efficiency take time to implement, through the adoption of smarter technologies and consumer products, along with education to facilitate behaviour change. Stronger policy strategies are greatly required in this area if long term targets are to be met.
- The introduction of shale gas to the UK needs careful management. There are clear benefits for implementing this technology, especially in terms of security of supply. Nonetheless, large expansion of this industry will deeply undermine steps to reach climate targets. What's more, many of the economic benefits often publicised relating to shale gas development in the UK could likely be equally met or surpassed by clean technology.

- Immediate action must be taken to eliminate recent doubt over the funding of carbon capture and storage. Even at moderate levels of installation, this technology proved essential to the low carbon future of the UK. This research shows that only through a large departure from the current regime can an adequate level of decarbonisation be achieved without this technology. Furthermore, increased reliance on gas generation must be halted until suitable support is in place.
- Quick coal generation phase-out only achieves moderate decarbonisation. This process must be balanced with long-term goals of the whole system. It may result in system lock-in to significant levels of gas generation capacity which could have been replaced with clean technology at a later date, ultimately resulting in lower GHG emissions across the full time horizon.
- Continued support for the production of biomethane is an important step in ensuring the long term decarbonisation of the gas grid. Even a modest influx was shown to offset rising emissions associated with future gas supplies.
- The emphasis and importance of gathering of quality LCA data is critical for novel technologies, especially as they advance from demonstration stage to full-scale deployment. Only then can a true assessment of the potential of these technologies to contribute to decarbonisation of the electricity sector be performed. Furthermore, greater environmental improvements are usually gained when employing LCA at this critical early design stage.
- Interdisciplinary modelling approaches proved essential in improving the robustness of this research. Projects of this nature need to be supported in order to develop the best solutions to the greatest current and future societal issues.

11.4 Future Work

Over the course of this research various areas requiring continued and parallel investigation were identified. These areas would complement this thesis work greatly, and help address some of its limitations. Examination of these areas would significantly enhance the evidence base within this portfolio of research, to develop strategies and support decision-making regarding transitioning electricity systems. The areas highlighted for further work are as follows:

- A full life cycle assessment of the entire UK energy system would allow different energy futures to be fully compared. The system boundaries would then be expanded to include both electricity and heat, circumventing allocation issues with combined heat and power. To date analysis has been carried out at this scale using aggregated methods, however, these methods don't provide the specific and detailed insight that is gained from process based LCA. Various data limitations must first be overcome supported by the growth of peer-reviewed LCA databases, which would be required to facilitate a larger energy system assessment.
- A key limitation of this work is the reliance on technology specific data, based on current day technology, subject to temporal and spatial constraints. Given the high level of uncertainty associated with performing future-oriented LCA of electricity systems, it was unreasonable to also predict the changes that may arise as a result of advancements in technology. However, work incorporating technology development research could be used to inform these datasets. Since uncertainty would be quite high, streamline LCAs could be performed to investigate potential variation in environmental performance. A series of sensitivity analyses should be conducted on key parameters which would likely change for the most critical technologies to delivering the required decarbonisation.
- Key technologies which should be prioritised for further assessment are gas generation and the more novel technologies such as carbon capture and storage, wave and tidal generation. Such research would be very complementary to this thesis and help indicate the potential changes in embodied impacts associated with technology when making proactive long-term investment decisions for the electricity sector. It could also help pinpoint critical areas for funding which are likely to gain significant advances environmental and not just economically.
- Gathering data for the more novel technologies was a challenge in this thesis. Strong liaison with technology developers and direct users could help address this significant data gap. Such research would be mutually beneficial, offering guidance at design stage, where LCA insights are proven to provide the most benefits.
- A full technical re-elaboration of the pathways as conducted and presented in article III and IV. To fully complete this process, this work should also feed into the re-elaboration

of the storylines. This would allow the issues raised by the interdisciplinary modelling to be fully addressed.

- Bioenergy was highlighted as a key potential method for deeper decarbonisation and supporting the decoupling of the electricity sector from fossil fuels. However, the sustainability of these resources moving forward into the future is highly uncertain. Furthermore, this limited resource will be in high demand across the economy as measures to attain deeper decarbonisation are implemented. Greater work is required to align bioenergy resource scenarios and future energy system modelling.

11.5 Concluding Remarks

Increasingly electrified economies, founded on truly decarbonised supply chains and generation technologies, is a fundamental step in supporting the global fight against climate change. This thesis has demonstrated that current decarbonisation strategies and policies are delivering less meaningful change in the fight against global warming than reported, as a result of inadequate accounting of upstream emissions. Additionally, all decarbonisation approaches assessed suggest that environmental compromises cannot be circumvented. These impacts varied significantly between each approach; all demonstrating their own areas of high environmental burdens. The research outputs illustrate the importance of considering the comprehensive total life cycle impacts of electricity generation when developing and implementing new decarbonisation policies, rather than direct fossil emissions alone. The impacts of future decarbonisation policies and measures must be balanced considering a wide spectrum of environmental issues in order to limit wider environmental damage.

Recent developments in the energy sector have seen significant shifts in ‘current thinking’ and approaches which have largely focused on meeting medium term targets. It is imperative that measures are now taken to develop a long-term strategic policy framework to deliver true decarbonisation, balanced across a wide spectrum of environmental metrics, whilst meeting broader system wide goals (technical, social, and economic aspects). Only then will a truly desirable transition to a low carbon future be secured, by providing the stability to induce greater investment in clean technologies, while also protecting the wider environment for generations to come.

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Appendix A: Article III

ELECTRONIC SUPPLEMENTARY MATERIAL

Linking a storyline with multiple models: a cross-scale analysis of the UK power system transition

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Table A.1. Revisiting the storyline with the multiple models. **Green** colour means that the model outputs are in line with the storyline, **yellow** – that there is a minor divergence, **red** – that the storyline statement contradicts the model outputs, **white** – the particular statement is not addressed in the model.

Relevant quotes from the storyline, taken from [37]	Demand	FESA	D-EXPANSE	EconA	BLUE-MLP	EEA	HESA/UK+	HAPSO
2008 -2022								
<p>“The major energy efficiency programmes are contributing to reducing levels of electricity demand.”</p> <p>“In addition, the government requires energy companies to install a ‘smart meter’ in every home by 2020, which helps to limit overall electricity demand.”</p> <p>“By 2020, the energy efficiency measures have led to the stabilisation of electricity demand.”</p>					A			
<p>“This policy involves a risk being passed to consumers of experiencing higher than average electricity costs, if the price of natural gas does not rise significantly.” Note: As the storyline does not specify more detail, the average electricity costs were measured in £(2010)/MWh and were compared to the costs levels of 2010.</p> <p>[The reduced levels of electricity demand] “mitigate unit electricity price rises, meaning that household energy bills only rise slowly.”</p>			B		C			
<p>“By 2020, <...> the relative decarbonisation of electricity supply has led to the achievement of the carbon budget of a 34% reduction in CO₂ emissions, compared to 1990 levels.”</p>						D		

"This is realised by the achievement of 25% of electricity to be generated from renewables by 2020."					E			
"High levels of deployment for onshore (8GW) and offshore wind, (10GW) which operates at over 40% capacity factor; the first operational CCS coal plant; and four new (1.6 GW) nuclear power stations."			F					G
2023 -2037								
"Remaining other coal and gas power stations are retired as they reach the end of their life."			H		I			J
"This leads to the further penetration of onshore and offshore wind (though at a lower rate of deployment than in earlier periods) and scaling up of wave and tidal power schemes, as a result of experience gained through earlier demonstration projects. The Severn tidal barrage, financed by a public-private partnership, also comes into operation by the mid 2020s."					K			L
"The commercial viability of CCS increases, thanks to earlier investment in demonstration projects and a high carbon price."			M					
"A total of 12 new (1.7 GW) nuclear power stations being in operation by 2030"			N		O			
"Energy service demand reduces, thanks to household and industrial energy efficiency measures"					P			

<p>"Significant improvements in domestic energy efficiency also result from the adoption of more efficient domestic appliances."</p> <p>"<...> a small reduction in industrial electricity use. This results from a decline in heavy emitting industries, as the UK's industrial base shrinks, and an improvement in energy efficiency of the remaining industrial processes."</p>							
<p>"Smart metering enables more dynamic management of demand, both by energy users in response to variable-time tariffs and by Distribution Network Operators, e.g. through managing demand from 'smart' appliances at peak times."</p> <p>"The [electric vehicle] fleets are coordinated to allow a proportion of them at any time to act as system regulators, to facilitate the penetration of high levels of inflexible generation. This system is having a major positive impact on grid management by distribution network operators by the 2030s."</p>							
"Domestic electricity demand rises due to the adoption of electric heating for 60% of domestic heating systems"							
"Overall, electricity demand only rises by just over 10% from 2020 to 2035"							
[From 2020 to 2035] "The carbon intensity of electricity generation improves significantly to less than 30 gCO ₂ /kWh (though higher when calculated on a life-cycle basis)"							

2038-2052								
<p>"Electricity demand rises but at a slower rate of increase, despite significant penetration of electric heating and electric vehicles, as consumers demand higher technical energy efficiency of appliances."</p> <p>"So, total electricity demand in 2050 is only 20% higher than in 2008."</p>					W			
"The deployment of both domestic and non-domestic distributed generation increases, meeting around a quarter of total demand by 2050, with significant shares from onshore wind and biomass CHP systems."	WW							
"The centralised generation system is now almost totally decarbonised, with eighteen large nuclear power plants with a total of 30 GW capacity providing the largest share of generation."			X		Y			
"There is significant further investment in CCS systems, resulting in 10GW of coal with CCS and 20 GW of gas with CCS by 2050"			X		Z			
"Overall, 65 GW of renewables capacity is installed, mainly onshore and offshore wind and wave and tidal power."			X		AA			
"The average carbon intensity of electricity generation has now been reduced to below 20 gCO ₂ /kWh by 2050, resulting in the almost complete decarbonisation of power generation, though carbon emissions are significantly higher when calculated on a life-cycle basis."						AB		AC

Key risks								
The key risk is that “Carbon capture and storage turns out to be technologically or economically unfeasible”			AD (Not key risk)					AE
The key risk is that “Higher energy service costs resulting from high levels of low-carbon investment.”			AF					
Notes: A: The BLUE-MLP model shows that, due to the behavioural inertia, there is only a 60% chance that power demand in 2020 will be less than 350TWh/year. B: The D-EXPANSE model considers a range of maximally different transition pathways and shows that this statement can be true or not: the costs and prices may rise, but also may fall, given certain technology choices. C: Although the power price in 2050, modelled by the BLUE-MLP model, is comparable to that in 2010, it can be up to 50% higher in the interim period due to the carbon price required to spur the diffusion of low emission technologies. D: According to the EEA, the greenhouse gas emissions from fuel burning meet the target as the emissions were reduced by 39.5% between 1990 and 2020. If the life-cycle emissions are considered, the target is missed (430 gCO ₂ /kWh). E: The share of renewable energy sources in 2020, modelled by the BLUE-MLP model, is smaller than 25% because the model prioritises nuclear for mitigating emissions. This is partly because the BLUE-MLP model has only one renewable energy source (offshore wind power), which is outperformed by nuclear. F: The described generation mix is only one of the modelled pathways in the D-EXPANSE model, but there is a large number of other, different mixes possible. There is a range of capacity factors, higher or lower than 40%, possible. G: The capacity factor for wind power, modelled in the HAPSO model, varies from 24% to 36% under different assumptions, but does not reach 40%. Thus, the economic								

feasibility of these generators is questioned.

H: The D-EXPANSE model shows a range of maximally different transition pathways, but in 2037 in all of these pathways there is 15 GW to 75GW of gas without CCS in a combination with up to 26 GW of coal without CCS. Thus, the complete retirement of all gas power plants in the storyline contrasts the minimum of 15GW in the D-EXPANSE.

I: The BLUE-MLP model evaluates the joint capacity of coal and gas power plants will be 24GW in 2037 and thus this capacity of these power plants will not be completely phased out (16% of the total installed capacity in the UK will remain).

J: The HAPSO model results in 15GW gas power plants and additional 40 GW gas OCGT plants in 2037. This is required in order to meet the power system balancing challenge, which, according to the model, is not possible without a considerable amount of gas power plants.

K: The BLUE-MLP model considers only one renewable energy source (offshore wind) as a representative technology for renewable energy sources. Its installed capacity in 2037 is 12 GW. Such a low deployment of offshore wind is due to the fact that it is outperformed in the near-term by nuclear in costs, and due to utilities continuing to invest in portfolios of new capacity based on expected developments in technology costs and carbon prices.

L: The HAPSO shows the deployment of 30GW of wind power in 2037, but no deployment of wave or tidal power, which is described in the storyline.

M: The D-EXPANSE model generates a large number of maximally different scenarios and there are several scenarios in this set with up to 25 GW of coal with CCS and up to 42GW of gas power plants with CCS. However, the absolute majority of scenarios have no coal or gas CCS, which indicates a smaller importance of wide CCS deployment.

N: The D-EXPANSE model considers a range of maximally different transition pathways and shows that this statement can be true, but the uptake of nuclear in 2037 can be from 10GW to 60GW.

O: In the BLUE-MLP model, the installed capacity of nuclear power in 2037 ranges from 8 GW all the way up to 90 GW and thus can considerably exceed the installed capacity from the storyline. As in the earlier point K, this is because BLUE-MLP has cost driven portfolios of new plant investment.

R: According to the FESA model, the average CO₂ emissions from fuel burning used in the UK power system in 2030 would be 54 gCO₂/kWh, which indicates that the carbon intensity value in 2035 may not be consistent with the storyline.

S: According to the BLUE model, the average CO₂ emissions from fuel burning used in the UK power system in 2037 would be 33 to 35 gCO₂/kWh and this is slightly higher than the value from the storyline.

T: The EEA evaluates that the greenhouse gas emissions in 2035 will be 120 gCO_{2eq}/kWh in the whole life cycle, of which 56 gCO_{2eq}/kWh will be the operational emissions. Therefore, the carbon intensity value for 2035 in the storyline would be missed.

U: The HESA/UK+ model results in the average CO₂ emissions of 36 gCO₂/kWh in 2035. This is slightly higher than the value for 2035 in the storyline.

V: The HAPSO model results in the average CO₂ emissions of 40 gCO₂/kWh in 2035, which is higher than the value from the storyline.

W: Owing to the extreme requirements to meet the CO₂ reduction targets, the BLUE-MLP model, finds that power demand is only stabilized in end-use sectors to 2035. Following this power demands rise as the need for low carbon electricity outweigh the efficiency and demand reductions (which are somewhat limited by the heterogeneous behaviour of the different actors

WW: According to the Demand model, distributed generation technologies, onshore wind, biomass, solar and CHP renewable contribute about 20% of the total power generation by 2050.

X: According to the D-EXPANSE model, which considers a range of maximally different transition pathways, the generation mix can be as described in the storyline, but there are also a broad range of other mixes possible.

Y: The BLUE-MLP model does find that the power sector is heavily decarbonised. However, the power sector is very large by 2050 with electrification of end-use sectors and the median of probabilistic model runs for the installed capacity in 2050 include 100GW of nuclear.

Z: The BLUE-MLP model does find that the power sector is heavily decarbonised, but includes only 30GW of renewables (represented by offshore wind).

AA: The BLUE-MLP model does find that the power sector is heavily decarbonised, but without any CCS plants.

AB: According to the HAPSO model, the average CO₂ emissions in 2050 are 21 gCO₂/kWh, which is only slightly higher than the value from the storyline. AC: The EEA evaluates the operational carbon intensity of power generation as 26 g CO_{2eq}/kWh in 2050.

AF: According to the HAPSO model, the average CO₂ emissions in 2050 are 21 gCO₂/kWh, which is only slightly higher than the value from the storyline.

AD: The feasibility of CCS is not the key risk according to the D-EXPANSE model. The model considers a range of maximally different transition pathways, of which some have a considerable share of CCS in the generation mix in 2050. However, there is a broad spectrum of other mixes possible, which perform roughly similar with respect to costs and emissions, but have no CCS. Thus, CCS and its feasibility is not the prerequisite for implementing this storyline.

AE: This is the key risk according to the HAPSO model. This model evaluates the capacity factors of gas power plants with CCS in 2050 to range from 17% to 51%. In the case of the low capacity factors, the economic feasibility of CCS would be indeed questioned.

AF: This can be a key risk, but does not have to be. D-EXPANSE model considers a range of maximally different transition pathways and generates a range of pathways that have lower energy service costs.

Appendix B: Article VI

The life cycle greenhouse gas implications of a UK gas supply transformation on a future low carbon electricity sector

Supplementary information

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1. Greenhouse gas emissions associated with different gas production routes

The ‘greenhouse gas’ (GHG) emissions associated with gas production can vary greatly from source to source, depending on the processes and energy resources used, the characteristics of the gas well, and the regulatory framework in a given location. Furthermore, gas from distant regions must undergo long transportation through pipelines, resulting in considerable fugitive emissions[1], or must undergo liquefaction, shipping and regasification: all energy intensive processes which result in additional GHG emissions being emitted. The data used for upstream emissions associated with different gas supply routes as delivered to gas-fired power plant, can be seen here in Table SI_ 1and Figure SI_ 1.

Table SI_ 1. Upstream GHG emissions data associated with gas supply routes by source (units in gCO₂eq/MJ)

Gas Supply Pathway	Central estimate	Confidence interval	
		Lower	Higher
UK	1.99	1.37	2.77
Norway	4.17	2.87	5.87
Netherlands	2.58	1.83	3.62
European Union Continent	5.12	3.57	6.99
2012 supply mix	4.73	3.33	6.35
Russian	20.30	11.40	33.20
Shale Gas	13.60	10.38	19.83
Bio 2020	17.91	16.05	28.95
Bio 2030	17.88	16.09	30.22
Bio 2050	20.84	19.19	30.10
Liquefied Natural Gas	18.10	12.96	23.23

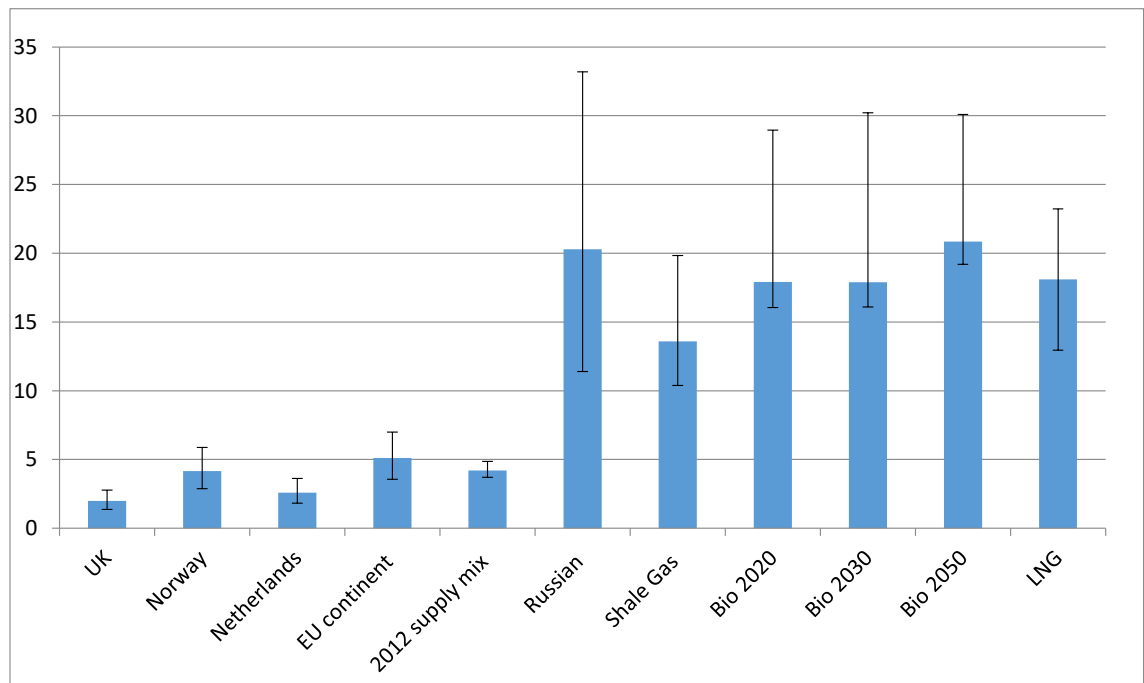


Figure SI_ 1. Upstream GHG emissions associated with gas supply pathway by source (units in gCO₂eq/MJ)

The system boundaries were aligned for all gas supply routes (see figure 1 in paper). Emissions were accounted from the extraction of gas (or cultivation of feedstock and collection of waste for biomethane), through processing (including liquefaction for LNG), long distance transport (where applicable), and finally the regional distribution in the UK to the gas-fired power plants.

1.1 Pipeline gas

The pipeline gas emissions for the various supply routes were taken from *Ecoinvent* database (version 2.2) which is widely considered, particularly in Europe, as the most comprehensive and transparent Life Cycle Inventory (LCI) database available[2]. In a review of energy related LCI data by the European commission, the *Ecoinvent* natural gas datasets were rated ‘very good’, achieving the top data quality rating with no relevant need for improvement. The majority of input data for this database is sourced from environmental reports and industry data with the assistance of industrial experts. The same methodological approach has been applied across all datasets, providing consistent data within harmonized system boundaries[3].

In order to limit the level of uncertainties in this analysis, it was assumed that the fuel supply chains (i.e. gas background systems/upstream processes) would remain the same as today’s route based on current available data. It is feasible that unconventional gas could be imported from

these regions by pipeline, but it would be very difficult to say at what level it would be expected to contribute. Given the infancy of unconventional gas in these regions, with some European countries currently instigating moratoria on the exploitation of unconventional gas, its contribution is unlikely to be significant in the short to medium term. In the long-term, it is realistic to expect a significant influx of unconventional gas from these sources, but again, given the current infancy of the shale gas industry in these regions, the potential percentage contribution of unconventional gas cannot reasonably be estimated. Consequently, it has been assumed that the gases sourced from these regions were all derived from natural gas out to 2050.

Monte Carlo simulations were carried out for each supply route in order to quantify the uncertainties related to each dataset. All input flow data was extracted from the *Ecoinvent* database for gas, include the uncertainty estimates. 1000 runs were carried out for each dataset, using randomly selecting values for inputs based on the uncertainty distributions. The resultant 90% interval probability distribution for each supply route was used to represent the range for that gas source.

The natural gas emissions data taken from the *Ecoinvent* database for these pipeline gas routes encompass the same system boundaries. The natural gas upstream chain include the following process stages within this boundary: gas production (which includes exploration, production at field, purification), long-distance transport and regional distribution to the power plants. A full account of the underlying assumptions of these datasets and the detailed analysis of the systems can be found in the associated *Ecoinvent* reports and papers[4-7].

1.2 Shale gas

A review was carried out by Weber and Clavin[8] of six studies concerning the life cycle carbon footprint associated with shale gas production. A Monte Carlo simulation was carried out, drawing inputs from across the studies in order to produce a best estimate range for each process step in shale gas production chain; the summation of these stages provided the figure for total GHG emissions of shale gas production. System boundaries and assumptions were aligned in an effort to produce an uncertainty distribution for shale gas production. This assessment was employed here to represent the potential GHG emissions of UK shale gas. All six studies assessed by Weber and Clavin were US based production, therefore, this data should only be considered as 'indicative' until real UK operational data becomes available.

Three main stages were assessed; preproduction, production/processing and transmission. The final process step was replaced with the UK regional distribution from *Ecoinvent* so as to

increase the consistency with the other gas production routes. A full account of the assumptions taken to produce this best estimate range of shale gas production are given by Weber and Clavin[8] and their supplementary information.

1.3 Liquefied Natural gas

Five studies[4, 9-12] were collated to produce an uncertainty distribution to represent the potential impacts of future LNG in the UK. The origin of future LNG could vary significantly, depending on the gas markets and the development in shale gas extraction internationally. Again, it was assumed here that all LNG were from conventional sources in order to reduce the uncertainties.

All data sources included the process stages of production, processing, liquefaction, transportation by LNG tanker and regasification and injection to the grid. The distribution of natural gas to power plants was replaced with the UK regional distribution from *Ecoinvent* to increase consistency across gas production routes. For Skone *et al.*[11], the distribution stage could not be separated from the aggregated LNG gas fuel chain emissions and was therefore left unchanged.

The median was chosen to represent the central tendency of the distribution of LNG gas in this study, instead of the average, in order to reduce the impact of outliers on the results due to the relatively small sample size of data available. This is common practice in statistics and has been used by others in the LCA field to represent the central tendency of a data distribution, including the IPCC[13]. A full account of the methodology used in these studies can be found in their respective papers and reports.

1.4 Biomethane use in the Transition Pathways

1.4.1 Production of Biomethane

Biomethane is generated by upgrading and purifying biogas from various forms of feedstocks; predominately from biowaste and energy crops. Two main processes are used in producing biogas: anaerobic digestion and thermochemical gasification. Anaerobic digestion is already in use in the UK and has experienced significant growth in recent years[14]. Gasification of biomass (residual wood) is remains at a research, development and demonstration (RD&D) stage, with demonstration plants now scaling up to 20MW in Sweden[15]. Given the uncertainty in the development of this technology, the biomethane supplies were modelled here as being sourced entirely from anaerobic digestion.

Table SI_ 2.The current feedstock for anaerobic digestion in the UK [taken from ADBA[14]]

Feedstock	Million wet tonnes (t)	Biogas yield ^a (m3/t FM)	Biogas Output (m3)	Percentage contribution to overall supply
Farm waste	1.0	56.0	56.0	2.7%
Industrial residues	6.1	80.0	488.0	23.6%
Crops	1.3	200.6	260.8	12.6%
Food waste	1.6	110.0	176.0	8.5%
Residual Waste	0.5	101.5	50.7	2.5%
Sewage Sludge	22.0	47.0	1034.0	50.1%

Large quantities of feedstock are required to produce biogas on a commercial scale; consequently, feedstocks are generally sourced in the local area, in order to avoid excessive transport costs and associated GHG emissions. In this analysis, it was therefore assumed that different feedstock would not change greatly from their current distribution. The current feedstock for anaerobic digestion in the UK is shown in Table SI_ 2. The percentage contribution was derived by assigning each feedstock category with an appropriate biogas yield to determine how much biogas would be produced from that feedstock. This enabled the contribution of each particular feedstock to the total feedstock overall supply to be determined. The biogas yield can vary significantly for different feedstocks within each category. Where a typical biogas yield was not available for a given category, the biogas yield of a typical feedstock was used, i.e. farm waste was based on manure, industrial residue was based on Draff from beer production, and the yield for crops was based on maize.

It is difficult to predict how this feedstock mix might evolve over time given the number of varying factors involved. Welfle *et al.*[16] developed scenarios for the potential biomass resource availability in the UK out to 2050. The potential feedstock breakdown out to 2050 was modelled according to their ‘energy focus’ scenarios.

^a Biogas yield take from
http://www.seai.ie/Renewables/Bioenergy/Bioenergy_Technologies/Anaerobic_Digestion/The_Process_and_Techniques_of_Anaerobic_Digestion/Gas_Yields_Table.pdf

Table SI_ 3. Percentage breakdown between grown, residue and waste resources^b

biomass resources	2014	2020	2030	2050
grown	12.63%	23.61%	23.57%	33.77%
residue	23.63%	18.70%	12.67%	11.08%
waste	63.75%	57.69%	63.76%	55.15%
total	100%	100%	100%	100%

Table SI_ 4. Generated biomethane feedstock mixes for 2020, 2030 and 2050

Feedstock	Percentage Contribution			
	2014	2020	2030	2050
Farm waste	2.7%	2.5%	2.7%	2.4%
Industrial residues	23.6%	18.7%	12.7%	11.1%
Crops	12.6%	23.6%	23.6%	33.7%
Food waste	8.5%	7.7%	8.5%	7.4%
Residual Waste	2.5%	2.2%	2.5%	2.1%
Sewage Sludge	50.1%	45.3%	50.1%	43.3%
total	100%	100%	100%	100%

The total biomass resources were split into three main categories: grown, residue and waste resources across the entire economy. Although some of the biomass feedstock included in each of these three categories would not be suitable for biomethane production, the percentage breakdown between these three groups was used, as a proxy, for the future availability of feedstock for biomethane. The proportion of grown resources was modelled as crops, and the

^b 2014 mix was derived from feedstocks in table 1 .Mix 2020,2030 and 2050 were calculated based on the biomass resources modelled for each given year for the energy focus scenario.

residues were modelled as industrial residue. The waste resources were modelled using a scaled weighted percentage of the current feedstock mix from waste sources (mix 2014 in Table SI_ 3). Accordingly, a feedstock mix was generated for 2020, 2030 and 2050 (see Table SI_5).

1.4.2 Technical potential UK biomethane yield

Biomethane can be produced from a range of feedstocks, and be an effective process to deal with costly waste, potentially turning it into a valuable resource, and even a source of revenue. The technical biomethane potential could be very high, due to the diverse range of feedstocks that can be used to produce this energy source[15]. However, it is difficult to estimate the technical potential of this resource for the UK given the large uncertainties involved.

Electricity generated from biomethane, via gas-fired generation or combined heat and power, plays a significant role in all three transition pathways. Total electricity generation produced from biomethane in a given Transition Pathway, for each gas supply mix, is shown below in Table SI_ 5.

Table SI_ 5. Total electricity generation from biomethane in the Transition Pathways

Year	Biomethane penetration %	Supply Mix	Market Rules (TWh)	Central Coordination (TWh)	Thousand Flowers (TWh)
202	5	Supply mix	26.2	32.2	79.0
	10	Supply mix	34.8	39.9	84.0
	5	Supply mix	26.2	32.2	79.0
203	5	Supply	28.5	30.5	128.1
	18	Supply mix	46.8	51.3	136.1
	5	Supply mix	28.5	31.8	128.1
205	5	Supply mix	39.8	38.5	144.1
	25	Supply mix	57.5	51.8	146.7
	10	Supply mix	44.2	41.9	144.7

At its peak in 2050, biomethane-related generation accounts for 47 TWh of electricity produced under the MR pathway, 51TWh in CC pathway, and 147 TWh in TF pathway respectively. These figures included both generation from CHP and also penetration of biomethane into the gas mix for gas-fired generation. The *Thousand Flowers* pathway leads to the consumption of far more biomethane than its counterparts, due to the critical role of CHP in that pathway[17]. By 2050, half of electricity generation is produced from distributed energy generators under the TF pathway. Accordingly, CHP will no longer only be used as a heat-led technology, but increasingly electrically-led. Thus, it would carry out important grid balancing duties in conjunction with DSP.

An assessment carried out on the bioenergy power generation potential across the entire UK economy has suggested that delivering biomethane for MR and CC pathways electricity sectors would be foreseeable even for the more conservative scenarios[16] (as seen in Table SI_ 6). However, to deliver the required biomethane for the electricity sector under the TF pathway, although possible, would be rather ambitious and require prioritising bioenergy specifically for the purpose of electricity generation. Table SI_ 6 summarizes energy generation across the UK economy, and not just the electricity, which is the focus of this work.

Table SI_ 6. The bioenergy generation potential for the United Kingdom taken from [taken from Welfle *et al.*[16]]

The bioenergy generation potentials of available resources (TW h).							
Year	Food focus	Economic focus	Conservat - ion focus	Energy focus (balanced conversion)	Energy focus (heat prioritised)	Energy focus (power prioritised)	Energy focus (transport fuel prioritised)
2015	54.66	49.09	49.51	79.31	91.45	72.53	59.70
2020	75.36	58.83	59.87	151.59	178.27	131.00	98.25
2030	154.20	113.25	114.10	312.62	349.90	263.30	181.63
2050	338.18	251.25	261.15	541.48	593.00	440.74	289.06

1.4.3 GHG emissions associated with biomethane

GHG emissions associated with biomethane are primarily dependent on the feedstock and the conversion technology used in its production[18]. For waste and residual feedstocks, upstream GHG emissions are not accounted for until after the point of collection[19]. Three GHG emissions datasets for biomethane produced from manure, municipal waste and maize were used from the European Commission's *Joint Research Centre* (JRC) database[10] to account for the six feedstock categories discussed. The emissions data for manure was used to account for farm waste, and was also used as a proxy for sewage sludge. The emissions were scaled based on the relative ratio between their biogas yields. Municipal waste was used to account for residual waste, and then scaled in the same manner for food waste and industrial residue, based on the relative ratio of their biogas yield. Maize is the most commonly used energy crop[20], and was used here to account for crop feedstocks.

These GHG emissions data for the production of biomethane were taken from the JRC database again developed for the European Commission in order to account for the energy and GHG balance for different fueling routes for transport powertrains from well-to-tank. Thus, the final stage of compression and dispensing of the gas was not included and was instead replaced by a biomethane injection stage as modelled by Adams *et al.*[20] for the UK. It was assumed during this process that 0.01 MJ of electricity from the UK grid was consumed per 1 MJ of biomethane injected. No emissions credits have been included for methane avoided through the use of waste streams. Likewise, the methane emissions credit was not included from the GHG emissions data used for manure.

The biogas yield for feedstocks can vary significantly depending on the inputs. A range in emissions for these feedstocks was determined using a Monte Carlo simulation, with uncertainties assigned to inputs, in order to develop a plausible range of variation for the total pathway. Given the large variability associated with biogas production routes[18], these ranges were used to account for the uncertainties and potential variation in the quality of feedstocks.

2. Recent trends in UK gas supply

The UK has experienced a considerable change in gas supply over the past few years (as seen in **Error! Reference source not found.**), moving away from indigenous gas as North Sea resources diminished. LNG imports have grown significantly since 2005, after a 20 years hiatus, with two new LNG terminals becoming operational in 2009. Despite this growth, imports from Norway and Netherlands (through a new interconnector that became operational in 2006) remain critical suppliers of gas for the UK. Britain has consequently become increasingly dependent on foreign gas over the past decade. Some of the major trends that are likely to have a significant impact on the evolution of UK gas supply are as follows:

- **Increasing Asian demand.** It is widely believed that the LNG market is likely to tighten[21] over the coming years, due to high Asian demand. Gas imports from Qatar and Australia are likely to be increasingly expensive for European consumers, due to increasing competition from countries such as India, Pakistan, Thailand, China, Taiwan, Japan and South Korea.
- **Diminishing reserves in European Union (EU).** Demand for gas has increased across Europe over the last decade, and the disparity between production and consumption continues to grow. An 87% increase in gas imports into the EU is anticipated between 2006 and 2030 to meet the growing indigenous deficit[22].
- **Unconventional gas sources.** New contributors to the gas supply market, such as biomethane and shale gas, are likely to become available over the coming years. The first commercial biogas connection began injecting into the UK national grid in December 2013[23]. However, biogas is a limited resource (in terms of waste and sustainable energy crops) in Britain[24]. In light of recent success in America, shale gas is being explored by many countries across Europe. Intense production processes brings large environmental and social concerns[25], making shale gas unlikely to contribute significantly to supply before 2020. The UK shale gas production may grow significantly in the longer-term, if indigenous and Continental Europe gas supplies are exploited in the future[26].
- **LNG exports from USA and Canada.** After the recent shale gas boom in North America, production is set to exceed consumption, with the US planning to export LNG by 2016. Seven export terminals, equating to 12.5% of US production capacity have been

approved with many more proposed[27]. Uncertainty remains over what level of exports will occur in the future, and what impact they will make on the global market.

- **UK gas storage facilities.** The UK role as a significant North Sea natural gas producer has resulted in little investment in gas storage capacity. Without substantial growth in domestic gas storage, the UK will have to act strategically as the fuel supply evolves, especially as Norwegian and Dutch production declines. Seasonal flexibility will be crucial as the British ESI moves to more intermittent generation. UK may then have to outsource its supply flexibility to neighbouring countries, where large storage facilities are under construction[28].
- **Variability in UK gas demand.** Gas demand may well fall over the coming decade as the UK transitions to a more low carbon economy[29] with the heating sector and industry becoming increasingly electrified, and improvements in energy efficiency are implemented. Some analysts[30] forecast that gas demand could rise in the medium term, due to heightened demand for power generation in order to facilitate this transition. All three transition pathways envisage a reduction in gas demand for electricity generation[31]. Interestingly, ESI under the *Thousand Flowers* pathway demonstrates the largest dependence on gas, albeit principally biomethane required for CHP generation. The *Market Rules* pathway has a slightly higher dependence on natural gas than under its *Central Coordination* counterpart, due to its larger overall electricity demand, and higher penetration of gas-fired power generation with CCS in its generation portfolio. All projections, irrespective of core driving principles or governance logic, include gas as a significant part in future UK energy mixes.

3. Future gas supply scenarios

Three future gas mix scenarios were developed based on the future trends in this paper. These mixes were developed for explorative means only, and do not attempt to predict the future or steer the future gas market.

The main assumptions and trends for each case study are:

Supply 1: UK Shale gas ‘boom’. In this future, it is assumed that shale gas extraction takes off in the UK and becomes the primary gas resource. Reliance on other gas sources will reduce,

with a stable contribution maintained in the interest of security of supply. In this future, it is assumed that LNG will be the main source of imports, with Russian imports reduced, due to political tensions in that region. A moderate penetration of bio-methane continues as part of the mix in order to tackle bio-waste.

Supply 2: High biomethane and LNG supply. In the event of a shale gas moratorium, biomethane would be more heavily developed to provide an indigenous supply of gas. Again, in this future, it is assumed that LNG will be the main source of imports, with Russian imports again reduced, due to political tensions in that region.

Supply 3: High Russian gas dependence. This future assumes a shale gas moratorium in the UK. Biomethane is limited, due to environmental pressures (such as those associated with land use). Asian demand for LNG gas increases dramatically, because of the reduction in nuclear power plants being built (e.g., in Japan), constraining LNG supplies. Consequently, Russia would become a critical gas supplier to Europe.

A list of the main assumptions and background data used to develop the three gas supply scenarios used in this paper are set out below:-

1.4.4 UK production and import dependency

- UK gas supply mix 2012 figures were taken from *Digest of UK Energy Statistics* 2013[32].
- The UK Government's *Department of Energy and Climate Change* (DECC) projects that Britain will have a gas import dependency of 57% by 2020, and 76% by 2030[33], which is also in line with the *National Grid* (NG) future scenarios[30].
- This import dependency was assumed for the high Russian gas scenario with a reduced dependency used for the other two supply scenarios due to growth in domestic supply.
- Import dependency could be reduced from 76% to 37% by 2030 should shale gas reach its potential[34].
- Imports are accounted for as net imports, but with same proportion of import dependency as stated in the *Digest of UK Energy Statistics* (DUKES) 2013[32].

- Gas flows to the UK were projected to be broadly in line with domestic production trends in each particular exporting country.
- The number of fields expected to be in operation in UKCS post 2050 even out to 2060 according to *Oil and Gas UK*[35]. However, this will be at a relatively low production rate. It was assumed to supply only 5% of overall demand in 2050.

1.4.5 *European gas imports*

- Imports ceased from Netherlands after 2020, due to its indigenous production decline[28]. Indeed, the IEA[36] forecast that Netherlands would be a net importer by 2025.
- Norwegian gas imports into the UK reached peak by 2014 and declined thereafter[28].
- Norwegian gas imports for 2020 and 2030 were taken from NG ‘*Gone Green*’ scenario taken from their UK future energy scenarios work[30]
- In 2020, other EU imports were based on NG imports proposed in their ‘*Gone Green*’ scenario [30]
- An 87% increase in gas imports into the EU is anticipated between 2006 and 2030 to meet the growing deficit[22].
- The split between European and Russian gas was then based on import assumptions for Europe in 2020, 2030 and 2050.

1.4.6 *Shale gas*

- Shale gas moratorium assumed for both Supply 2 and 3 in this paper.
- Shale gas production in 2020 based on ‘reference case’ production assumptions in the Deloitte report on the potential of Bowland basin shale gas development[37].
- Shale gas could provide up to 46 years of gas based on assumptions made by the NG[30].
- Only domestic shale gas has been considered in this analysis, shale gas imported from Continental Europe has not been considered.

1.4.7 *Biogas*

- For Supply 1, biogas is not incentivised due to environmental pressures (such as land use), thus remains the same as at present; i.e. only produced for bio-waste management.
- Assumed baseline projection by NG[24] for biogas for Supply 1 and 3 in 2020, while its 'stretch' scenario was used for Supply 2. This stretch scenario is taken to be near maximum biogas potential of the UK.

1.4.8 *Russian gas*

- Russia remains the world's largest energy exporter, meeting 4% of global energy demand by 2035[38].
- Russian gas was set as minimum of 2.4 billion cubic metres based on contract written by *Centrica* in 2012, they were set to start importing by October 2014[39].
- In 2020, Russia gas is swing source in Supply 3 similar to that assumed for the analysis by Rogers[28], thus meeting the shortfall.
- The ratio in 2020 between European and Russian gas stays the same across all supply scenarios.
- Europe's gas import dependency is expected to rise from 60% to more than 80% by 2035[40]. Therefore imports from the gas pipeline are split 1/3 European (indigenous) to 2/3 Russian-based gas in 2030, based on the projected decline in European gas production. Imports from the gas pipeline are split 20% European (indigenous) to 80% Russian-based gas for supply 3 in 2030, in accordance with this high Russian gas future.
- In 2050, Imports from the pipeline are split 15% European (indigenous) to 85% Russia-based gas for Supply 3, based on similar assumptions to those made for the 2030 supply extrapolated into the future. Russian gas was presumed to be the dominant imported gas source for Supply 3.

1.4.9 *Liquefied natural gas*

- LNG was assumed to grow slowly out to 2020, due to tightness expected in the market over the coming years as a result of greater Asian demand for gas[21].
- For Supply 1, LNG and pipeline gas imports were split 50/50 in 2030 and 2050, in the interest of diversity of supply.
- For Supply 2, LNG and pipeline gas imports were split 75/25 in 2030 and 2050, as LNG is dominated supply in this scenario.
- For Supply 3, LNG was seen to only grow slowly from its 2012 levels as LNG supply is constrained in this future.

4. Detailed life cycle GHG results for the Transition Pathways

In this section, total life cycle GHG emissions are provided for all three pathways for the baseline gas mix and gas Supply 1-3, along with a breakdown of emissions by life cycle stage. The range in upstream emissions is also provided basis on the uncertainty ranges as described in SI_section 2. A table is also included showing the reduction in direct emissions from baseline for the three Transition Pathways due to the penetration of biomethane.

Table SI_ 7. Life cycle GHG emissions for Market Rules (MR) pathway when paired with three future gas supply mixes, broken down into stages.

Market Rules - million tonnes of CO _{2eq} emissions							
Supply mix		Total emissions	Direct	Upstream Gas	Upstream other	Upstream gas negative bar	Upstream gas positive bar
2020	Base	168.89	139.79	6.56	22.54	0.00	0.00
	Supply 1	168.31	136.50	9.27	22.54	2.40	4.11
	Supply 2	164.83	133.21	9.08	22.54	1.74	5.02
	Supply 3	167.60	136.50	8.56	22.54	1.95	5.09
2030	Base	77.84	48.81	6.56	22.46	0.00	0.00
	Supply 1	81.79	47.09	12.24	22.46	2.94	3.19
	Supply 2	74.00	37.72	13.82	22.46	3.24	6.70
	Supply 3	82.79	45.73	14.60	22.46	4.79	7.87
2050	Base	50.61	21.02	6.08	23.51	0.00	0.00
	Supply 1	56.16	18.91	13.74	23.51	2.71	6.04
	Supply 2	50.07	10.47	16.09	23.51	3.19	6.53
	Supply 3	56.15	16.80	15.84	23.51	4.36	7.82




























Table SI_ 8. Life cycle GHG emissions for Central Coordination (CC) pathway when paired with three future gas supply mixes, broken down into stages.

Central Coordination - million tonnes of CO ₂ eq emissions							
Supply mix		Total emissions	Direct	Upstream Gas	Upstream other	Upstream gas negative	Upstream gas positive
2020	Base	146.43	120.04	6.04	20.66	0.00	0.00
	Supply 1	148.90	118.79	9.45	20.66	2.31	5.75
	Supply 2	146.29	115.76	9.86	20.66	2.34	4.62
	Supply 3	148.94	118.79	9.48	20.66	2.59	4.63
2030	Base	48.57	30.13	6.37	12.14	0.00	0.00
	Supply 1	51.05	27.30	11.60	12.14	2.74	5.79
	Supply 2	43.94	18.20	13.60	12.14	3.08	6.96
	Supply 3	52.85	26.81	13.89	12.14	4.44	7.67
2050	Base	28.08	11.58	5.40	11.10	0.00	0.00
	Supply 1	32.54	9.99	11.45	11.10	2.13	5.06
	Supply 2	27.80	3.63	13.07	11.10	2.50	5.43
	Supply 3	32.49	8.40	12.99	11.10	3.38	6.40

Table SI_ 9. Life cycle GHG emissions for *Thousand Flowers* (TF) pathway when paired with three future gas supply mixes, broken down into stages.

Thousand Flowers - million tonnes of CO _{2eq} emissions							
Supply mix		Total emissions	Direct	Upstream Gas	Upstream other	Upstream gas negative	Upstream gas positive
2020	Base	119.73	93.29	9.06	17.66	0.00	0.00
	Supply 1	121.37	91.39	12.32	17.66	2.15	6.67
	Supply 2	119.36	89.49	12.21	17.66	1.77	6.50
	Supply 3	121.39	91.39	12.34	17.66	2.33	6.81
2030	Base	37.98	15.23	12.83	10.07	0.00	0.00
	Supply 1	42.25	13.81	18.38	10.07	2.71	11.36
	Supply 2	39.30	10.12	19.11	10.07	2.86	11.88
	Supply 3	43.35	13.81	19.48	10.07	3.58	12.43
2050	Base	22.98	4.04	12.41	6.53	0.00	0.00
	Supply 1	30.26	3.72	20.01	6.53	1.93	8.95
	Supply 2	29.33	2.44	20.37	6.53	2.01	9.03
	Supply 3	30.26	3.40	20.33	6.53	2.18	9.35

Table SI_ 10. Reduction in direct emissions from baseline for the Transition Pathways for 2020, 2030 and 2050

Million tonnes of CO ₂ eq emissions				
Year	Supply	MR	CC	TF
2020	Supply 1	 3.29	 1.25	 1.90
	Supply 2	 6.59	 4.28	 3.80
	Supply 3	 3.29	 1.25	 1.90
2030	Supply 1	 1.73	 2.82	 1.42
	Supply 2	 11.10	 11.93	 5.11
	Supply 3	 3.08	 3.31	 1.42
2050	Supply 1	 2.11	 1.59	 0.32
	Supply 2	 10.55	 7.95	 1.60
	Supply 3	 4.22	 3.18	 0.64

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Appendix C: Article VIII

The potential environmental consequences of shifts in energy policy for electricity generation

Supplementary Information

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1. Electricity demand

Table SI_1. Demand at supply point of use for the three pathways

Year	Market Rules (TWh)	Central Coordination (TWh)	Thousand Flowers (TWh)
2008	376.12	376.7277	376.1225
2010	364.27	373.615	362.8699
2015	368.7	352.6137	348.0659
2020	397.245	359.315	340.5071
2025	427.639	379.4958	347.3549
2030	456.083	394.5334	357.1457
2035	477.792	400.4264	350.2639
2040	499.069	405.4962	354.4483
2045	519.2965	413.2866	357.7535
2050	539.501	419.6665	358.204

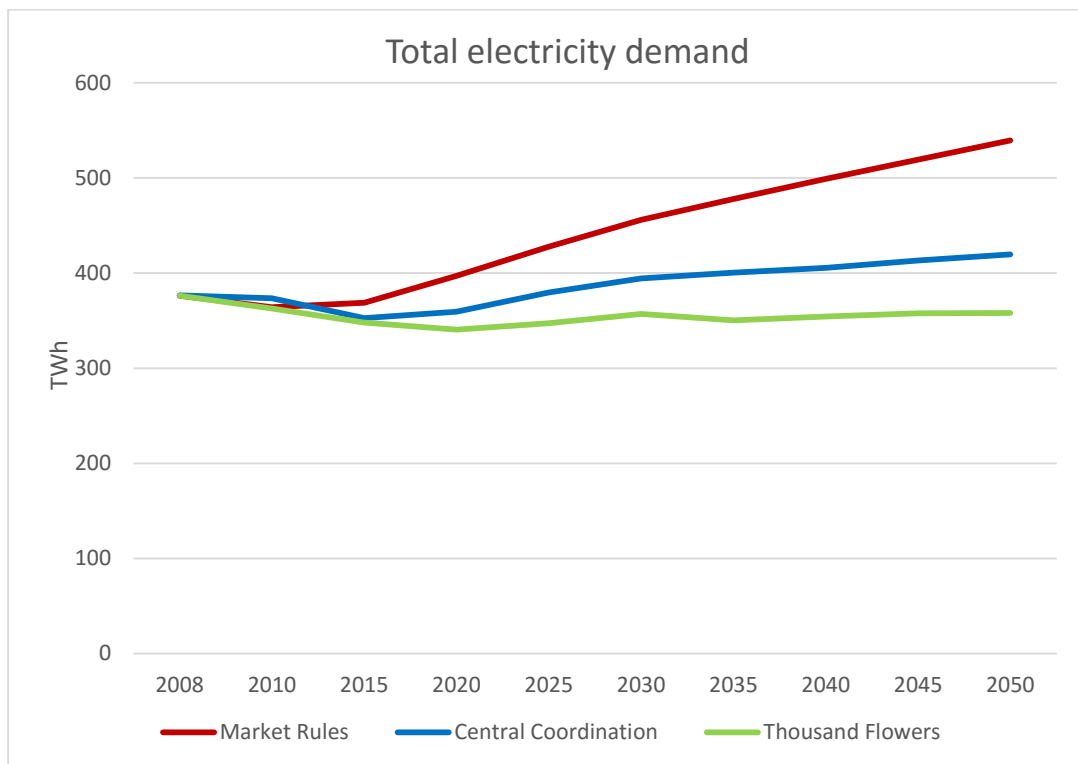


Figure SI_1. Total electricity demand at supply point of use for the three pathways from 2008 to 2050.

2. Overview of ReCiPe methodology, midpoint indicators and associated units.

In this study, the Hierarchical perspective was chosen in order to quantify environmental impacts are in line with scientific consensus and accounting for a mean level of risk.

Table SI_2 Overview of environmental impacts assessed using ReCiPe methodology

Impact Category	Midpoint indicator	Unit	Description
Climate change (IPCC 2007 AR4)	Global warming potential	kg CO₂ eq	Climate change refers to the change in global temperature caused by the greenhouse effect by the release of 'greenhouse gases'. The reference unit is carbon dioxide equivalent.
Ozone depletion	Stratospheric ozone concentration	kg CFC-11 eq	Ozone-depleting gases cause damage to stratospheric ozone or the 'ozone layer'. The reference unit is kilograms of chlorofluorocarbon-11 (CFC-11) equivalent.
Human toxicity	Hazard-weighted dose	kg 1,4-DB eq	The emission of some substances (such as heavy metals) can have impacts on human health. Assessments of toxicity are based on tolerable concentrations in air, water, air quality guidelines, tolerable daily intake and acceptable daily intake for human toxicity. The reference unit is kilograms of 1,4-dichlorobenzene (1,4-DB) equivalent.
Photochemical oxidant formation	Photochemical ozone concentration	kg NMVOC	The release of substances into the atmosphere which react with sunlight to produce low level ozone or also known as 'summer smog'. This smog is associated with crop damage and respiratory diseases. The reference unit is kilograms of non-methane volatile organic carbon compound (NMVOC).
Particulate matter formation	PM10 intake	kg PM10 eq	The emission of primary and secondary particles increases particulate matter (PM) formation which is damaging to human health. The reference unit is kilograms of particulate matter.
Ionising radiation	Absorbed dose	kg U235 eq	The release of radioactive material can cause damage to human health and the environment. The reference unit is kilograms Uranium 235 equivalents.
Terrestrial acidification	Base saturation	kg SO₂ eq	Inorganic emissions such as sulfates, nitrates, and phosphates cause atmospheric acid deposition which in turn can change the acidity of soil and result in damage to ecosystems. The reference unit is kilograms of sulphur dioxide equivalent.
Freshwater	Phosphorous	kg P eq	The emission of some substances, such

eutrophication	concentration		as phosphorus, nitrogen, ammonia and nitrogen oxide can result in the over-enrichment of freshwater. The reference unit is kilograms of phosphorus equivalent.
Marine eutrophication	Nitrogen concentration	kg N eq	The emission of some substances, such as phosphorus, nitrogen, ammonia and nitrogen oxide can result in the over-enrichment of sea water. The reference unit is kilograms of nitrogen equivalent
Terrestrial ecotoxicity	Hazard-weighted concentration	kg 1,4-DB eq	The emission of some substances, such as heavy metals, can have impacts on the terrestrial ecosystems. Assessment of toxicity has been based on maximum tolerable concentrations for ecosystems. The reference unit is kilograms of 1,4-dichlorobenzene (1,4-DB) equivalent.
Freshwater ecotoxicity	Hazard-weighted concentration	kg 1,4-DB eq	The emission of some substances, such as heavy metals, can have impacts on the freshwater aquatic ecosystems. Assessment of toxicity has been based on maximum tolerable concentrations for ecosystems. The reference unit is kilograms of 1,4-dichlorobenzene (1,4-DB) equivalent.
Marine ecotoxicity	Hazard-weighted concentration	kg 1,4-DB eq	The emission of some substances, such as heavy metals, can have impacts on the marine aquatic ecosystems. Assessment of toxicity has been based on maximum tolerable concentrations for ecosystems. The reference unit is kilograms of 1,4-dichlorobenzene (1,4-DB) equivalent.
Agricultural land occupation	Occupied area	m² x yr (agricultural land)	The amount of agricultural land occupied for a certain time. The reference unit is metres squared years.
Urban land occupation	Occupied area	m² x yr (urban land)	The amount of urban land occupied for a certain time. The reference unit is metres squared years.
Natural land transformation	Transformed area	m² (natural land)	The amount of natural land transformed and occupied for a certain time. The reference unit is metres squared years.
Water depletion	Water use	m³	Amount of water consumed measured. The reference unit is metres cubed of water extracted.
Metal depletion	Grade decrease	kg Fe eq	The amount of metal extracted. The reference unit is kg Iron (Fe) equivalent.
Fossil depletion	Energy content	kg oil eq	The amount of fossil fuel extracted, based on the lower heating value. The unit is kg oil equivalent.

3. Characterised Life cycle impact results for the three pathways

Table SI_3 – Abbreviations used in Tables SI_4 to Table SI_9

Impact Category	unit	SI Table Abbreviation
Climate Change	kg CO ₂ eq	CC
Ozone Depletion	kg CFC-11 eq	Ozone Depl.
Human Toxicity	kg 1,4-DB eq	Human Tox.
Photochemical Oxidant Formation	kg NMVOC	Photo Oxi.
Particulate Matter Formation	kg PM10 eq	PM
Ionising Radiation	kg U235 eq	Ion. Rad.
Terrestrial Acidification	kg SO ₂ eq	Terr. Acid.
Freshwater Eutrophication	kg P eq	FW Eutroph.
Marine Eutrophication	kg N eq	M Eutroph.
Terrestrial Ecotoxicity	kg 1,4-DB eq	Terr. Ecotox.
Freshwater Ecotoxicity	kg 1,4-DB eq	FW Ecotox.
Marine Ecotoxicity	kg 1,4-DB eq	Marine Ecotox.
Agricultural Land Occupation	m ² a	Agri. Land
Urban Land Occupation	m ² a	Urban Land
Natural Land Transformation	m ²	Natural Land
Water Depletion	m ³	Water Depl.
Metal Depletion	kg Fe eq	Metal Depl.
Fossil Depletion	kg oil eq	Fossil Depl.

Table SI_ 4. Characterised LCIA results for Original Market Rules

Market Rules - Characterised Environmental Life Cycle Impact Assessment, Ecoinvent V2.2											
	1990	2008	2010	2015	2020	2025	2030	2035	2040	2045	2050
CC	2.5E+11	2.2E+11	2.1E+11	2.0E+11	1.8E+11	1.4E+11	9.2E+10	6.8E+10	6.3E+10	6.2E+10	6.2E+10
Ozone Depl.	6.0E+03	7.1E+03	7.8E+03	7.8E+03	7.7E+03	7.6E+03	7.3E+03	7.1E+03	6.8E+03	6.9E+03	6.9E+03
Human Tox.	8.9E+10	5.9E+10	5.3E+10	5.0E+10	5.4E+10	6.0E+10	6.4E+10	6.7E+10	7.0E+10	7.1E+10	7.4E+10
Photo Oxi.	6.7E+08	4.5E+08	4.0E+08	3.6E+08	3.7E+08	4.0E+08	4.0E+08	4.0E+08	3.9E+08	3.9E+08	4.0E+08
PM	3.8E+08	2.3E+08	1.9E+08	1.7E+08	1.8E+08	1.9E+08	2.0E+08	2.1E+08	2.1E+08	2.1E+08	2.2E+08
Ion. Rad.	7.6E+10	6.2E+10	6.3E+10	4.4E+10	6.5E+10	8.6E+10	1.1E+11	1.2E+11	1.4E+11	1.5E+11	1.6E+11
Terr. Acid.	1.3E+09	7.3E+08	5.8E+08	5.1E+08	5.4E+08	6.0E+08	6.3E+08	6.4E+08	6.4E+08	6.5E+08	6.7E+08
FW Eutroph.	1.1E+08	5.4E+07	4.8E+07	4.3E+07	4.6E+07	5.1E+07	5.4E+07	5.6E+07	5.7E+07	5.8E+07	6.0E+07
M Eutroph.	2.4E+08	1.6E+08	1.4E+08	1.3E+08	1.3E+08	1.4E+08	1.4E+08	1.4E+08	1.4E+08	1.4E+08	1.4E+08
Terr. Ecotox.	1.3E+07	1.3E+07	1.1E+07	1.2E+07	1.2E+07	1.3E+07	1.4E+07	1.5E+07	1.5E+07	1.5E+07	1.5E+07
FW Ecotox.	1.7E+09	9.4E+08	8.3E+08	7.6E+08	8.3E+08	9.3E+08	9.9E+08	1.0E+09	1.1E+09	1.1E+09	1.1E+09
Marine Ecotox.	1.8E+09	1.1E+09	9.4E+08	8.7E+08	9.4E+08	1.0E+09	1.1E+09	1.1E+09	1.2E+09	1.2E+09	1.2E+09
Agri. Land	5.0E+09	6.7E+09	6.1E+09	5.9E+09	6.2E+09	6.7E+09	7.6E+09	8.0E+09	7.7E+09	7.5E+09	7.4E+09
Urban Land	1.5E+09	1.0E+09	8.9E+08	8.0E+08	8.5E+08	9.5E+08	1.0E+09	1.0E+09	1.0E+09	1.0E+09	1.1E+09
Natural Land	2.6E+07	4.2E+07	4.0E+07	4.1E+07	3.9E+07	3.8E+07	3.6E+07	3.6E+07	3.2E+07	3.1E+07	3.0E+07
Water Depl.	1.1E+09	1.0E+09	9.9E+08	8.5E+08	9.8E+08	1.1E+09	1.3E+09	1.3E+09	1.4E+09	1.5E+09	1.6E+09
Metal Depl.	7.2E+09	9.3E+09	9.1E+09	9.4E+09	1.0E+10	1.2E+10	1.3E+10	1.4E+10	1.5E+10	1.5E+10	1.6E+10
Fossil Depl.	6.9E+10	7.5E+10	7.2E+10	6.9E+10	6.9E+10	7.0E+10	6.8E+10	6.8E+10	6.4E+10	6.3E+10	6.3E+10

Table SI_ 5. Characterised LCIA results for Original Central Coordination

Central Coordination - Characterised Environmental Life Cycle Impact Assessment, Ecoinvent V2.2											
	1990	2008	2010	2015	2020	2025	2030	2035	2040	2045	2050
CC	2.5E+11	2.2E+11	2.2E+11	2.0E+11	1.6E+11	1.2E+11	5.5E+10	4.1E+10	4.1E+10	3.6E+10	3.6E+10
Ozone Depl.	6.0E+03	7.1E+03	8.1E+03	7.2E+03	6.6E+03	6.8E+03	6.8E+03	6.6E+03	6.4E+03	6.3E+03	6.1E+03
Human Tox.	8.9E+10	5.9E+10	5.4E+10	5.2E+10	5.1E+10	4.9E+10	4.7E+10	4.6E+10	4.8E+10	4.8E+10	5.0E+10
Photo Oxi.	6.7E+08	4.5E+08	4.0E+08	3.9E+08	3.5E+08	3.0E+08	2.4E+08	2.1E+08	2.2E+08	2.0E+08	2.0E+08
PM	3.8E+08	2.3E+08	1.9E+08	1.9E+08	1.7E+08	1.5E+08	1.2E+08	1.1E+08	1.1E+08	1.1E+08	1.1E+08
Ion. Rad.	7.6E+10	6.2E+10	7.0E+10	4.6E+10	6.8E+10	8.7E+10	1.4E+11	1.5E+11	1.5E+11	1.8E+11	1.8E+11
Terr. Acid.	1.3E+09	7.3E+08	5.9E+08	5.8E+08	5.2E+08	4.4E+08	3.5E+08	3.2E+08	3.4E+08	3.1E+08	3.3E+08
FW Eutroph.	1.1E+08	5.4E+07	4.9E+07	4.8E+07	4.4E+07	3.9E+07	3.3E+07	3.0E+07	3.2E+07	3.1E+07	3.3E+07
M Eutroph.	2.4E+08	1.6E+08	1.4E+08	1.4E+08	1.2E+08	1.1E+08	8.5E+07	7.6E+07	8.0E+07	7.1E+07	7.4E+07
Terr. Ecotox.	1.3E+07	1.3E+07	1.2E+07	1.1E+07	1.1E+07	1.2E+07	1.2E+07	1.2E+07	1.2E+07	1.2E+07	1.2E+07
FW Ecotox.	1.7E+09	9.4E+08	8.5E+08	8.3E+08	7.9E+08	7.2E+08	6.5E+08	6.2E+08	6.5E+08	6.4E+08	6.7E+08
Marine Ecotox.	1.8E+09	1.1E+09	9.6E+08	9.3E+08	8.9E+08	8.2E+08	7.5E+08	7.2E+08	7.5E+08	7.4E+08	7.7E+08
Agri. Land	5.0E+09	6.7E+09	6.1E+09	6.3E+09	5.8E+09	5.8E+09	6.0E+09	5.9E+09	5.6E+09	5.1E+09	5.1E+09
Urban Land	1.5E+09	1.0E+09	9.1E+08	9.1E+08	8.2E+08	7.0E+08	5.8E+08	5.3E+08	5.6E+08	5.2E+08	5.6E+08
Natural Land	2.6E+07	4.2E+07	4.1E+07	3.8E+07	3.2E+07	3.3E+07	2.9E+07	2.8E+07	2.7E+07	2.3E+07	2.1E+07
Water Depl.	1.1E+09	1.0E+09	1.0E+09	8.7E+08	9.3E+08	1.0E+09	1.3E+09	1.3E+09	1.3E+09	1.4E+09	1.5E+09
Metal Depl.	7.2E+09	9.3E+09	9.3E+09	9.0E+09	9.6E+09	1.0E+10	1.1E+10	1.2E+10	1.2E+10	1.2E+10	1.3E+10
Fossil Depl.	6.9E+10	7.5E+10	7.4E+10	6.9E+10	6.0E+10	5.6E+10	4.6E+10	4.3E+10	4.3E+10	3.7E+10	3.6E+10

Table SI_6. Characterised LCIA results for Original Thousand Flowers

Thousand Flowers - Characterised Environmental Life Cycle Impact Assessment, Ecoinvent V2.2											
	1990	2008	2010	2010	2010	2010	2010	2010	2010	2010	2010
CC	2.5E+11	2.2E+11	2.1E+11	1.8E+11	1.4E+11	9.0E+10	5.7E+10	4.6E+10	3.9E+10	3.8E+10	3.8E+10
Ozone Depl.	6.0E+03	7.1E+03	8.0E+03	7.2E+03	7.3E+03	6.9E+03	6.0E+03	4.6E+03	3.5E+03	3.5E+03	3.5E+03
Human Tox.	8.9E+10	5.9E+10	5.1E+10	5.0E+10	4.6E+10	4.4E+10	4.2E+10	4.1E+10	4.0E+10	4.0E+10	4.0E+10
Photo Oxi.	6.7E+08	4.5E+08	3.8E+08	3.7E+08	3.2E+08	2.7E+08	2.2E+08	1.9E+08	1.6E+08	1.6E+08	1.6E+08
PM	3.8E+08	2.3E+08	1.8E+08	1.7E+08	1.5E+08	1.3E+08	1.1E+08	1.1E+08	9.9E+07	9.6E+07	9.6E+07
Ion. Rad.	7.6E+10	6.2E+10	6.2E+10	4.4E+10	3.2E+10	3.4E+10	3.7E+10	3.5E+10	3.4E+10	3.3E+10	3.3E+10
Terr. Acid.	1.3E+09	7.3E+08	5.4E+08	5.3E+08	4.7E+08	4.3E+08	3.9E+08	3.8E+08	3.7E+08	3.6E+08	3.5E+08
FW Eutroph.	1.1E+08	5.4E+07	4.5E+07	4.4E+07	3.8E+07	3.4E+07	3.0E+07	2.9E+07	2.7E+07	2.7E+07	2.7E+07
M Eutroph.	2.4E+08	1.6E+08	1.3E+08	1.3E+08	1.1E+08	9.6E+07	8.1E+07	7.2E+07	6.4E+07	6.2E+07	6.1E+07
Terr. Ecotox.	1.3E+07	1.3E+07	1.1E+07	1.1E+07	1.3E+07	1.3E+07	1.4E+07	1.4E+07	1.4E+07	1.4E+07	1.4E+07
FW Ecotox.	1.7E+09	9.4E+08	7.9E+08	7.8E+08	6.9E+08	6.4E+08	5.9E+08	5.7E+08	5.5E+08	5.4E+08	5.4E+08
Marine Ecotox.	1.8E+09	1.1E+09	9.0E+08	8.8E+08	7.8E+08	7.2E+08	6.7E+08	6.4E+08	6.1E+08	6.1E+08	6.1E+08
Agri. Land	5.0E+09	6.7E+09	5.8E+09	4.6E+09	6.6E+09	7.9E+09	9.4E+09	1.0E+10	1.1E+10	1.1E+10	1.1E+10
Urban Land	1.5E+09	1.0E+09	8.4E+08	8.2E+08	7.0E+08	6.1E+08	5.4E+08	5.1E+08	4.8E+08	4.6E+08	4.6E+08
Natural Land	2.6E+07	4.2E+07	4.2E+07	3.8E+07	2.9E+07	2.5E+07	2.1E+07	1.6E+07	1.4E+07	1.4E+07	1.3E+07
Water Depl.	1.1E+09	1.0E+09	9.8E+08	8.3E+08	6.2E+08	5.7E+08	5.3E+08	4.8E+08	4.5E+08	4.4E+08	4.4E+08
Metal Depl.	7.2E+09	9.3E+09	9.0E+09	8.9E+09	9.4E+09	1.0E+10	1.1E+10	1.1E+10	1.1E+10	1.1E+10	1.1E+10
Fossil Depl.	6.9E+10	7.5E+10	7.2E+10	6.7E+10	5.4E+10	4.5E+10	3.6E+10	2.9E+10	2.3E+10	2.3E+10	2.2E+10

4. Characterised life cycle impact results with coal phase out

Table SI_ 7.Characterised LCIA Results for Market Rules with Coal Phase Out

Market Rules, <u>Coal Phase Out</u> - Characterised Environmental Life Cycle Impact Assessment									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
CC	2.1E+11	2.0E+11	1.6E+11	8.3E+10	6.8E+10	5.0E+10	4.4E+10	4.4E+10	4.4E+10
Ozone Depl.	7.8E+03	7.8E+03	8.7E+03	6.6E+03	9.4E+03	9.3E+03	9.0E+03	9.1E+03	9.1E+03
Human Tox.	5.3E+10	5.0E+10	4.3E+10	3.6E+10	3.9E+10	4.1E+10	4.4E+10	4.6E+10	4.8E+10
Photo Oxi.	4.0E+08	3.6E+08	2.7E+08	1.2E+08	1.7E+08	1.7E+08	1.6E+08	1.6E+08	1.6E+08
PM	1.9E+08	1.7E+08	1.1E+08	4.7E+07	6.3E+07	6.5E+07	6.5E+07	6.7E+07	6.8E+07
Ion. Rad.	6.3E+10	4.4E+10	6.4E+10	8.4E+10	1.0E+11	1.1E+11	1.4E+11	1.5E+11	1.6E+11
Terr. Acid.	5.8E+08	5.1E+08	3.2E+08	1.1E+08	1.5E+08	1.6E+08	1.6E+08	1.6E+08	1.6E+08
FW Eutroph.	4.8E+07	4.3E+07	2.9E+07	1.7E+07	1.8E+07	1.9E+07	2.0E+07	2.1E+07	2.2E+07
M Eutroph.	1.4E+08	1.3E+08	9.3E+07	4.1E+07	6.0E+07	6.0E+07	5.7E+07	5.7E+07	5.6E+07
Terr. Ecotox.	1.1E+07	1.2E+07	1.2E+07	1.2E+07	1.3E+07	1.3E+07	1.4E+07	1.4E+07	1.4E+07
FW Ecotox.	8.3E+08	7.6E+08	5.7E+08	3.8E+08	4.3E+08	4.6E+08	4.9E+08	5.1E+08	5.4E+08
Marine Ecotox.	9.4E+08	8.7E+08	6.9E+08	4.9E+08	5.8E+08	6.1E+08	6.4E+08	6.7E+08	6.9E+08
Agri. Land	6.1E+09	5.9E+09	4.9E+09	3.9E+09	4.8E+09	5.0E+09	4.8E+09	4.5E+09	4.4E+09
Urban Land	8.9E+08	8.0E+08	5.1E+08	2.0E+08	2.6E+08	2.7E+08	2.8E+08	2.8E+08	2.9E+08
Natural Land	4.0E+07	4.1E+07	4.5E+07	3.0E+07	4.9E+07	4.8E+07	4.5E+07	4.4E+07	4.3E+07
Water Depl.	9.9E+08	8.5E+08	9.2E+08	8.1E+08	1.1E+09	1.2E+09	1.3E+09	1.4E+09	1.4E+09
Metal Depl.	9.1E+09	9.4E+09	1.0E+10	1.1E+10	1.3E+10	1.4E+10	1.5E+10	1.5E+10	1.6E+10
Fossil Depl.	7.2E+10	6.9E+10	6.3E+10	3.5E+10	5.6E+10	5.5E+10	5.1E+10	5.1E+10	5.0E+10

Table SI_8. Characterised LCIA Results for Central Coordination with Coal Phase Out

Central Coordination, <u>Coal Phase Out</u> - Characterised Environmental Life Cycle Impact Assessment									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
CC	2.2E+11	2.0E+11	1.4E+11	8.6E+10	4.3E+10	3.4E+10	3.3E+10	3.0E+10	2.9E+10
Ozone Depl.	8.1E+03	7.2E+03	7.5E+03	8.2E+03	7.8E+03	7.4E+03	7.3E+03	7.1E+03	7.0E+03
Human Tox.	5.4E+10	5.2E+10	4.1E+10	3.2E+10	3.5E+10	3.6E+10	3.7E+10	3.8E+10	3.9E+10
Photo Oxi.	4.0E+08	3.9E+08	2.5E+08	1.5E+08	1.3E+08	1.2E+08	1.2E+08	1.1E+08	1.1E+08
PM	1.9E+08	1.9E+08	1.1E+08	5.3E+07	5.3E+07	5.3E+07	5.3E+07	5.2E+07	5.1E+07
Ion. Rad.	7.0E+10	4.6E+10	6.7E+10	8.5E+10	1.4E+11	1.5E+11	1.5E+11	1.8E+11	1.8E+11
Terr. Acid.	5.9E+08	5.8E+08	3.2E+08	1.3E+08	1.3E+08	1.3E+08	1.3E+08	1.2E+08	1.2E+08
FW Eutroph.	4.9E+07	4.8E+07	2.9E+07	1.5E+07	1.6E+07	1.6E+07	1.6E+07	1.7E+07	1.7E+07
M Eutroph.	1.4E+08	1.4E+08	8.7E+07	5.2E+07	4.6E+07	4.4E+07	4.3E+07	3.9E+07	3.8E+07
Terr. Ecotox.	1.2E+07	1.1E+07	1.1E+07	1.1E+07	1.2E+07	1.2E+07	1.1E+07	1.1E+07	1.1E+07
FW Ecotox.	8.5E+08	8.3E+08	5.6E+08	3.5E+08	3.8E+08	4.0E+08	4.0E+08	4.2E+08	4.3E+08
Marine Ecotox.	9.6E+08	9.3E+08	6.6E+08	4.8E+08	5.0E+08	5.1E+08	5.2E+08	5.3E+08	5.4E+08
Agri. Land	6.1E+09	6.3E+09	4.6E+09	3.8E+09	4.6E+09	4.7E+09	4.3E+09	4.0E+09	3.9E+09
Urban Land	9.1E+08	9.1E+08	5.1E+08	2.1E+08	2.3E+08	2.3E+08	2.3E+08	2.3E+08	2.3E+08
Natural Land	4.1E+07	3.8E+07	3.7E+07	4.2E+07	3.5E+07	3.3E+07	3.3E+07	2.8E+07	2.7E+07
Water Depl.	1.0E+09	8.7E+08	8.7E+08	9.4E+08	1.2E+09	1.3E+09	1.3E+09	1.4E+09	1.4E+09
Metal Depl.	9.3E+09	9.0E+09	9.5E+09	1.0E+10	1.1E+10	1.2E+10	1.2E+10	1.2E+10	1.2E+10
Fossil Depl.	7.4E+10	6.9E+10	5.5E+10	4.9E+10	4.1E+10	3.8E+10	3.8E+10	3.2E+10	3.1E+10

Table SI_9. Characterised LCIA Results for Thousand Flowers with Coal Phase Out

Thousand Flowers, Coal Phase Out Scenario - Characterised Environmental Life Cycle Impact Assessment									
	2010	2015	2020	2025	2030	2035	2040	2045	2050
CC	2.1E+11	1.8E+11	1.3E+11	7.1E+10	5.0E+10	4.1E+10	3.4E+10	3.4E+10	3.3E+10
Ozone Depl.	8.0E+03	7.2E+03	8.0E+03	8.1E+03	6.8E+03	5.3E+03	4.1E+03	4.0E+03	4.0E+03
Human Tox.	5.1E+10	5.0E+10	3.7E+10	3.1E+10	3.3E+10	3.3E+10	3.4E+10	3.4E+10	3.4E+10
Photo Oxi.	3.8E+08	3.7E+08	2.4E+08	1.5E+08	1.4E+08	1.2E+08	1.0E+08	1.0E+08	1.0E+08
PM	1.8E+08	1.7E+08	1.0E+08	5.9E+07	6.1E+07	6.0E+07	6.1E+07	6.1E+07	6.0E+07
Ion. Rad.	6.2E+10	4.4E+10	3.1E+10	3.3E+10	3.6E+10	3.4E+10	3.4E+10	3.3E+10	3.2E+10
Terr. Acid.	5.4E+08	5.3E+08	3.1E+08	1.9E+08	2.1E+08	2.2E+08	2.4E+08	2.4E+08	2.3E+08
FW Eutroph.	4.5E+07	4.4E+07	2.6E+07	1.5E+07	1.7E+07	1.7E+07	1.7E+07	1.8E+07	1.8E+07
M Eutroph.	1.3E+08	1.3E+08	8.3E+07	5.3E+07	4.9E+07	4.4E+07	4.1E+07	4.1E+07	4.0E+07
Terr. Ecotox.	1.1E+07	1.1E+07	1.2E+07	1.3E+07	1.4E+07	1.3E+07	1.3E+07	1.3E+07	1.4E+07
FW Ecotox.	7.9E+08	7.8E+08	5.0E+08	3.5E+08	3.7E+08	3.8E+08	3.9E+08	4.0E+08	4.0E+08
Marine Ecotox.	9.0E+08	8.8E+08	6.0E+08	4.4E+08	4.7E+08	4.6E+08	4.7E+08	4.8E+08	4.8E+08
Agri. Land	5.8E+09	4.6E+09	5.6E+09	6.4E+09	8.3E+09	9.4E+09	1.0E+10	1.0E+10	9.9E+09
Urban Land	8.4E+08	8.2E+08	4.5E+08	2.2E+08	2.5E+08	2.6E+08	2.7E+08	2.7E+08	2.7E+08
Natural Land	4.2E+07	3.8E+07	3.3E+07	3.1E+07	2.6E+07	2.0E+07	1.7E+07	1.7E+07	1.7E+07
Water Depl.	9.8E+08	8.3E+08	5.8E+08	5.0E+08	4.8E+08	4.3E+08	4.1E+08	4.0E+08	4.0E+08
Metal Depl.	9.0E+09	8.9E+09	9.3E+09	1.0E+10	1.1E+10	1.1E+10	1.1E+10	1.1E+10	1.1E+10
Fossil Depl.	7.2E+10	6.7E+10	5.0E+10	3.9E+10	3.2E+10	2.4E+10	2.0E+10	2.0E+10	1.9E+10

5. Characterised Life cycle impact results for TF pathway with different fuel type and allocation

Table SI_10. Life cycle impact assessment results for each TF 2050 system; for the system with both biomass and biogas fuelled-CHP with the three allocation methods applied. [The blue bars allow the results for each environmental categories to be compared visually across the different CHP assumptions. The blue bars are scaled based on the largest contributor to an impact category.]

Thousand flowers 2050 system - Characterised Environmental Life Cycle Impact Assessment							
Impact category	Unit	TF biogas (DUKES)	TF biomass (DUKES)	TF biogas (Energy)	TF biomass (Energy)	TF biogas (Exergy)	TF biomass (Exergy)
Climate change	kg CO2 eq	3.78E+10	3.18E+10	3.29E+10	2.73E+10	4.43E+10	3.90E+10
Ozone depletion	kg CFC-11 eq	3.46E+03	2.78E+03	3.16E+03	2.67E+03	3.87E+03	3.00E+03
Human toxicity	kg 1,4-DB eq	4.04E+10	6.82E+10	3.95E+10	5.42E+10	4.14E+10	8.90E+10
Photochemical oxidant formation	kg NMVOC	1.59E+08	2.00E+08	1.47E+08	1.64E+08	1.74E+08	2.57E+08
Particulate matter formation	kg PM10 eq	9.57E+07	9.97E+07	8.67E+07	8.42E+07	1.08E+08	1.24E+08
Ionising radiation	kg U235 eq	3.27E+10	2.73E+10	3.09E+10	2.70E+10	3.51E+10	2.79E+10
Terrestrial acidification	kg SO2 eq	3.53E+08	2.87E+08	3.03E+08	2.43E+08	4.20E+08	3.55E+08
Freshwater eutrophication	kg P eq	2.68E+07	2.72E+07	2.61E+07	2.60E+07	2.76E+07	2.90E+07
Marine eutrophication	kg N eq	6.13E+07	7.23E+07	5.56E+07	5.85E+07	6.91E+07	9.35E+07
Terrestrial ecotoxicity	kg 1,4-DB eq	1.40E+07	2.22E+08	1.38E+07	1.24E+08	1.43E+07	3.63E+08
Freshwater ecotoxicity	kg 1,4-DB eq	5.43E+08	5.63E+08	5.28E+08	5.33E+08	5.62E+08	6.13E+08
Marine ecotoxicity	kg 1,4-DB eq	6.13E+08	6.61E+08	5.97E+08	6.19E+08	6.30E+08	7.29E+08
Agricultural land occupation	m2a	1.06E+10	2.14E+10	8.22E+09	1.26E+10	1.39E+10	3.41E+10
Urban land occupation	m2a	4.64E+08	6.20E+08	4.31E+08	4.97E+08	5.08E+08	8.03E+08
Natural land transformation	m2	1.35E+07	1.39E+07	1.29E+07	1.29E+07	1.43E+07	1.57E+07
Water depletion	m3	4.36E+08	3.89E+08	4.17E+08	3.82E+08	4.60E+08	4.01E+08
Metal depletion	kg Fe eq	1.14E+10	1.07E+10	1.11E+10	1.07E+10	1.18E+10	1.09E+10
Fossil depletion	kg oil eq	2.25E+10	2.07E+10	2.16E+10	2.04E+10	2.36E+10	2.14E+10